NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

O939

THREE-DIMENSIONAL ANALYSIS OF
SYNOPTIC SATELLITE AND
CONVENTIONAL METEOROLOGICAL OBSERAVATIONS

by

Douglas D. Owen

March 1988

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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION / AVAILABILITY OF REPORT Approved for public release; distribution is unlimited
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Naval Postgraduate School 6b. OFFICE SYMBOL (If applicable) 63	7a. NAME OF MONITORING ORGANIZATION Naval Postgraduate School
6c. ADDRESS (City, State, and ZIP Code) Monterey, California 93943-5000	7b. ADDRESS (City, State, and ZIP Code) Monterey, California 93943-5000
8a. NAME OF FUNDING / SPONSORING ORGANIZATION 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO / TASK NO / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)

THREE-DIMENSIONAL ANALYSIS OF SYNOPTIC SATELLITE AND CONVENTIONAL METEOROLOGICAL OBSERVATIONS

12. PERSONAL AUTHOR(S)
Douglas D. Owen

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Master's Thesis	FROM ________ TO ________	March, 1988	104

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Three-dimensional display, Three-dimensional analysis Meteorological three-dimensional graphics

19. ABSTRACT (Continue on reverse if necessary and identify by block number) This thesis presents applications for three-dimensional displays of clouds and conventional meteorological observations. Several views of a well developed squall line over the Gulf of Mexico on 9 April 1984 are presented to demonstrate the effectiveness of an improved three-dimensional display process. The squall line is analyzed using enhanced GOES infrared imagery, space shuttle photography, and three-dimensional cloud scenes to demonstrate the capability of the three-dimensional software to highlight the vertical structure of clouds. Also, a procedure to incorporate displays of atmospheric thermodynamic variables into the three-dimensional cloud displays has been developed. The surfaces added to the cloud displays include: constant height levels, constant pressure levels, and levels of constant potential temperature. These surfaces illustrate the usefulness of the display technique for analyzing the three-dimensional structure of the atmosphere. Additionally, a technique has been developed to use lifting condensation levels as a "first guess" for the base heights of the clouds. Cloud bases determined from lifting condensation levels represent a more realistic approach of determining cloud base topography than the previous method of using a single "flat base" for all the clouds in the three-dimensional display. Detailed appendices are included to demonstrate the software used and developed in this thesis.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL C. H. Wash	22b. TELEPHONE (Include Area Code) (408)-646-2295 22c. OFFICE SYMBOL 63Wx

DD FORM 1473, 84 MAR 83 APR edition may be used until exhausted. All other editions are obsolete

SECURITY CLASSIFICATION OF THIS PAGE

☆ U.S. Government Printing Office: 1986—606-24.

Three-dimensional analysis of Synoptic Satellite and Conventional Meteorological Observations

by

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN METEOROLOGY

from the

NAVAL POSTGRADUATE SCHOOL
March 1988

ABSTRACT

This thesis presents applications for three-dimensional displays of clouds and conventional meteorological observations. Several views of a well developed squall line over the Gulf of Mexico on 9 April 1984 are presented to demonstrate the effectiveness of an improved three-dimensional display process. The squall line is analyzed using enhanced GOES infrared imagery, space shuttle photography, and three-dimensional cloud scenes to demonstrate the capability of the three-dimensional software to highlight the vertical structure of clouds. Also, a procedure to incorporate displays of atmospheric thermodynamic variables into the three-dimensional cloud displays has been developed. The surfaces added to the cloud displays include: constant height levels, constant pressure levels, and levels of constant potential temperature. These surfaces illustrate the usefulness of the display technique for analyzing the three-dimensional structure of the atmosphere. Additionally, a technique has been developed to use lifting condensation levels as a "first guess" for the base heights of the clouds. Cloud bases determined from lifting condensation levels represent a more realistic approach of determining cloud base topography than the previous method of using a single "flat base" for all the clouds in the three-dimensional display. Detailed appendices are included to demonstrate the software used and developed in this thesis.

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ACKNOWLEDGEMENTS

I would like to thank both of my thesis co-advisors, Prof. P. A. Durkee and Prof C. H. Wash, for their encouragement and assistance in completing this thesis. Not only were they excellent advisors, they are also both excellent teachers that I enjoyed learning from during my education at the Naval Postgraduate School.

Additionally, this thesis would not have been possible without the dedication and support given to the new Interactive Digital Environmental Analysis (IDEA) Lab at the Naval Postgraduate School. This is an excellent facility that has greatly enhanced my knowledge in the field of three-dimensional computer graphics.

I also need to individually thank all the employees in the IDEA Lab for the extra effort they gave when I really needed their help. Thanks to: Doug Burks, Donna Burych, Lang Chou, Jim Cowie, Rick Khors, Craig Motell and Russ Schwanz. They all played an integral role in the success of this thesis.

Of course, my wife Hye Sok is the person who deserves the largest recognition for her support and understanding during the time I worked on this thesis. We may have missed out on some good times together, but I know she understands the importance of education and an accomplishment such as a thesis.

I. INTRODUCTION

Many sources of data (or products) are available for use by meteorologists to describe the atmosphere. Some of these products include surface weather maps, height contour maps of the atmosphere, radar summaries and various types of satellite imagery. New instruments such as Doppler radar, acoustic sounders and lidar are also continuously under development. Output from these new instruments will add to the list of products available as both input to numerical models and synoptic forecast tools.

As the volume and complexity of weather products continue to increase, it becomes more difficult for forecasters to use all the available data in a timely and effective manner. Part of this problem stems from the methods used to display forecast products. The majority of products are depicted in a two-dimensional chart format. For example, charts of constant geopotential height surfaces at standard pressure levels in the atmosphere are used to depict the strength and direction of the geostrophic wind over large areas of the globe. These and other two-dimensional charts must be mentally integrated by skilled meteorologists to create a three-dimensional model or image of the atmosphere in their mind.

Most of the major weather centers have already installed computerized graphic workstations that enable forecasters to display two-dimensional weather products and satellite imagery. Such workstations make it possible to quickly "flip through" numerous charts and speed up the preparation of forecasts. By overlaying several products, such as the 500 millibar (mb)

heights, 700 mb relative humidity (RH), and a satellite image, the forecaster can begin to understand the three-dimensional structure of the atmosphere. However, the meteorologist must still form a mental three-dimensional image of the atmosphere from the combination of two-dimensional products. It would be useful to have a computerized method which would directly present such integrated three-dimensional displays of weather products, omitting the need for time consuming studies of two-dimensional plots and maps (Hibbard *et al.*, 1987).

Over the past ten years several research techniques have been developed to display three-dimensional and four-dimensional images of selected atmospheric data, where the fourth dimension incorporates time into the display parameters. The first stereo method was demonstrated by Hasler *et al.*, (1979) as a method of producing a four-dimensional display of clouds from the Geostationary Operational Environmental Satellite (GOES) visible satellite data. Imagery from two GOES satellites is required to create a stereo image display. More recently, a three-dimensional display technique has been developed at the NASA/Goddard Space Flight Center (NASA/GSFC). This technique incorporates NOAA/Advanced Very High Resolution Radiometer (NOAA /AVHRR) one kilometer resolution infrared (IR) image data with a corresponding visible image pair. The IR data provides a 512 X 512 array of height fields. The visible image provides the necessary details for shading bright spots and shadows that show up in the satellite picture. These two images are then combined using a computer program that produces "perspective images" on image processing terminals. This technique produces very realistic three-dimensional images of clouds and can also be used to

display non-image data fields such as cloud top heights derived from other sources (Hasler *et al.*, 1985).

At the University of Wisconsin, Madison, a Man-computer Interactive Data Access System (McIDAS) based terminal is being developed to provide stereo views of animated sequences of four-dimensional weather data. This terminal uses two large screen projectors to create images for the left and right eyes using different polarization. An illusion of three-dimensionality is created in the display, and by using time-lapse loops, motion in the time domain is created. This technique integrates large quantities of four-dimensional meteorological data from satellite images, satellite and balloon soundings, doppler and volumetric radar, and conventional surface observations. These data are combined using shading, hidden surface removal, transparency, and stereo display geometry. According to Hibbard *et al.*, 1987, "this creates an illusion of a moving three-dimensional model of the atmosphere so vivid that you feel you can reach into the display and touch it."

At the University of California, Davis, Grotjahn (1987) has applied state-of-the-art computer graphics, designed for television advertising, to produce three-dimensional color plates and movies of several atmospheric features. The features he chose to depict in three-dimensions were wind trajectories, jet streams, fronts and RH as a cloud tracer. The three-dimensional graphics incorporate techniques for perspective, shadowing and graduation of color and shading to produce the best three-dimensional structure of the atmosphere presently feasible. This technique displays data within a "perspective box" in a manner similar to that being developed at the University of Wisconsin. The box has the scale in kilometers along its vertical

axis. Geopolitical boundaries and topography are drawn along the bottom of the box. The surface pressure pattern is also plotted on the bottom of the box to allow easy association of surface weather with upper air features (Grotjahn, 1987).

Instead of depicting clouds directly from data obtained by satellite imagery, Grotjahn uses a shading scheme to selectively shade-in regions of relative humidity higher than a certain cutoff value. The cutoff value varies with height in order to approximate the areal distribution of clouds. This technique is imperfect on a coarse grid but does facilitate the comparison between wind and moisture fields. However, this cloud display scheme lacks much detail when compared to actual satellite imagery.

Advanced computer graphics routines have also been applied at Colorado State University (CSU) to display meteorological satellite, radar and topography data in three-dimensions on high resolution graphic workstations. They use a commercially available general purpose computer graphics software package called MOVIE.BYU that was developed at Brigham Young University (BYU). At CSU, a method was developed to create uniquely defined finite element geometry models which closely approximate the shapes and dimensions of clouds and topography. These geometric models can be displayed by the BYU software which has very sophisticated algorithms for coloring, shading, rotating, scaling and other graphics techniques that produce realistic three-dimensional images. One of the desirable features of the BYU software is that it can be run on practically any host computer and is operating system independent. This makes it possible to use this software on virtually any computer system that has a graphics capability (Christiansen, *et al.*, 1987).

The technique developed at CSU was initially demonstrated by Meade (1985) as a method of displaying GOES images and Defense Mapping Agency (DMA) topography data for a 4.27° X 4.27° (approximately 256 X 256 nautical miles) area of the United States (U.S.). Modifications to the CSU software made it possible to incorporate 1-km resolution volumetric radar data into the display. This capability is very useful for studying relationships between cloud systems and regions within the clouds where varying intensities of precipitation occur (Craig, 1986). At the Naval Postgraduate School (NPS), another capability was added to allow the creation of geometry models of well defined parameters such as pressure or potential temperature surfaces within the atmosphere. This makes it possible to display these surfaces along with the clouds, so the meteorologist can look for spatial relationships between the atmospheric data and the weather that is occurring. The software changes at NPS also removed the restriction of using a 4.27° X 4.27° area of the earth to enable the display of much larger synoptic regions (Crosby, 1986).

The apparent resolution of the three-dimensional models had to be dramatically reduced to produce images of larger, synoptic regions of the U.S.. This was necessary for two reasons: 1) at that time, the MOVIE.BYU software was limited in the size of the model it could display, and 2) if the full resolution for clouds, topography and atmospheric data surfaces were used, the run times for production of the three-dimensional images would be significantly increased (Crosby, 1986).

In order to overcome these two problems, Crosby incorporated a simple averaging scheme. This scheme made it possible to "shrink" the data from a 512 X 512 satellite image into a 64 X 64 data array by averaging every eight

pixels in the X and Y directions into a single value or data point. While this technique overcame the restrictions of MOVIE.BYU, the resulting cloud models were very coarse and displayed a lack of realism for representing cloud features in the atmosphere. Fig. 1 is a three-dimensional image of clouds and two potential temperature surfaces produced with the modified version of the CSU software at NPS. Notice how clouds have a triangular tent appearance; this is the undesirable result of using the averaging scheme over a full resolution 512 X 512 satellite image.

One of the main goals of this thesis is to increase the resolution of the three-dimensional models. This was done by using a new version of MOVIE.BYU that allows generation of images at as high a resolution as desired, as long as the main executable program does not exceed the size limitations of the host computer system. By increasing the resolution of the cloud geometry models, a high degree of realism has been added to displays that incorporate synoptic-scale cloud features. Also, as part of this thesis, several new capabilities and improvements have been added to the software that produce three-dimensional models of clouds and atmospheric data. One of the new capabilities is an option for producing "cloud base topography." This topography is determined by using the heights of the lifting condensation level (LCL) throughout the geographic region defined by the satellite image of interest. The original CSU software that produced cloud geometry models only used a single height to represent the cloud base topography throughout the whole image. This resulted in the base of all clouds being a flat surface that did not vary within the display. While the cloud base topography can not always be defined from LCL data, this approach should improve the overall

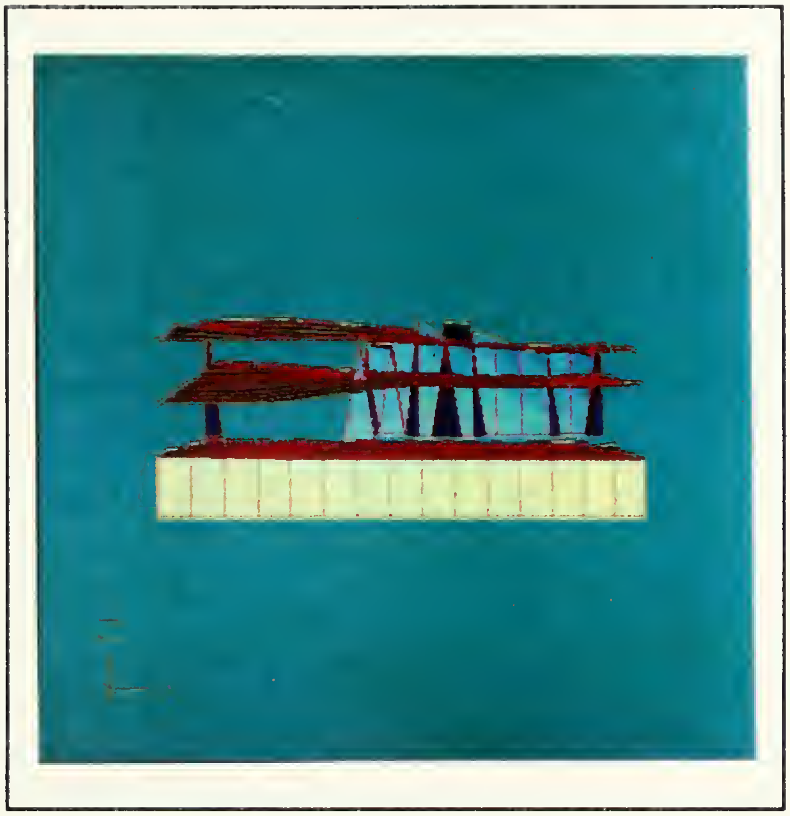


Fig. 1. Three-dimensional clouds and two potential temperature surfaces at 320 K and 340 K (Crosby, 1986).

realism of cloud geometry models by determining this topography from easily calculated thermodynamic parameters.

Additional improvements made to the CSU software were incorporated to make it more efficient and include "user friendly" menu options where possible. The CSU software was also modified to run under the Display Management Subsystem (DMS) of the Transportable Applications Executive (TAE). This graphics device management software package was developed at the NASA/GSFC (desJardins and Petersen, 1986). Graphic routines that use the DMS display package will run on any graphics workstation that has a TAE/DMS software interface. Thus, according to the Application Functions User's Guide for DMS (NASA, 1987), the DMS software is hardware independent. This now allows the three-dimensional graphics display software to be transported from one type of graphics workstation to another without any internal software modifications as long as the DMS interface software is available.

A squall line over the Gulf of Mexico on 9 April 1984 was chosen to demonstrate the potential usefulness of this three-dimensional display software for the analysis and interpretation of synoptic weather events. This case study was chosen because space shuttle photographs of the same squall line were available with a three-minute separation between the GOES IR/visible pair.

The following chapters explain the development of this three-dimensional software, the satellite and atmospheric data processing, and the application of this software to the 9 April 1984 squall line satellite imagery. Three-dimensional images depicting the heights of pressure levels and constant potential temperature surfaces also have been displayed along with the squall

line. These surfaces are useful to meteorologists for analyzing developing weather systems, instructing students, and briefing pilots on a proposed flight plans. Also, appendices are included to show the sequence of programs and commands necessary to produce a complete three-dimensional scene from GOES satellite imagery.

II. THEORY

A. REPRESENTING CLOUDS IN THREE-DIMENSIONS

The technique used in this thesis to create three-dimensional models of clouds involves determining the height, or Z coordinates, of the top and bottom of a cloud for all points within a two-dimensional array of X and Y coordinates that overlay the cloud to be modelled. These X, Y and Z coordinates are connected as a series of polygons, called a geometry model. When colored, shaded and drawn with perspective, they appear as a three-dimensional image of the original two-dimensional cloud scene.

This technique is similar to approximating a function of two variables, $y = f(x)$, by connecting a large number of $f(x)$ values at numerous closely spaced x grid points. Fig. 2 illustrates this concept. The shape of the function $y = \cos(x)$ is approximated by connecting straight lines between the points defined by the x and $f(x)$ function values separated by a grid spacing of 0.8 radians (Fig. 2a). However, a much better approximation is obtained by decreasing the grid spacing to 0.4 radians as shown in Fig. 2b.

This same technique can be extended to three-dimensions for approximating a surface that varies in space such as a sphere, or for this thesis, a cloud. Now instead of connecting lines between points, a series of three and four sided polygons are used to model the variations of the clouds surface. Each polygon becomes a finite element (FE) of the clouds geometry model, and the model begins to approximate the details of individual clouds as the spacing between polygons decreases. The spacing between polygons is

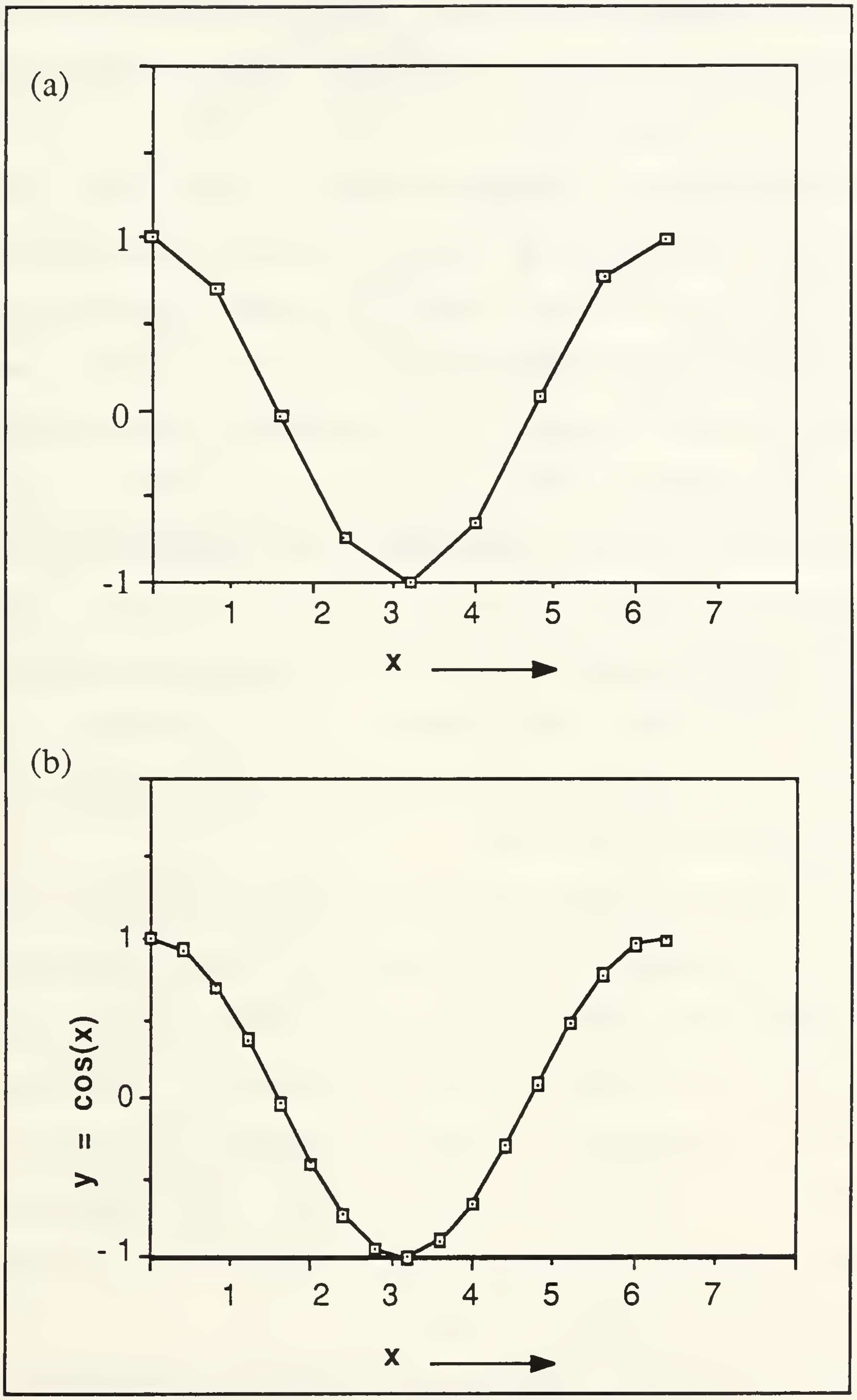


Fig. 2. Graphs of y = cos (x) for a grid spacing of .8 radians (a) and .4 radians (b).

decreased by incorporating more X, Y and Z coordinates from the satellite image of the cloud. Of course, the minimum spacing is limited by the spatial resolution of the satellite data.

A three-dimensional box, suspended in space, will be used to illustrate the data necessary to define geometry models for input to the MOVIE.BYU graphics software. There are six polygon elements that define the geometry of the box as seen in Fig. 3a. Each polygon defines one face of the box. Note that the polygons are connected at eight X, Y, Z coordinates. Each connection point is called a node. Therefore, a box consist of six polygons defined by eight X, Y, Z coordinate points connected at eight nodes. The coordinates that define this particular box are shown in Fig. 3b. The data are used as input to the MOVIE.BYU graphics program, DISPLAY, and must have a specific format as indicated by this example. The minus sign in the connectivity array is a flag to DISPLAY that indicates the last connection point or node of a particular polygon (Christiansen, *et al.*, 1987).

The first step in representing clouds as a series of polygons is to obtain all the X, Y, Z coordinate points of the clouds in the region of interest. Meade (1985) developed the software that processes GOES IR satellite imagery and determines the cloud top heights at evenly spaced X and Y grid points. Cloud top heights are determined by relating IR brightness temperatures (IRTBS) to the height on an atmospheric sounding where these temperatures occur. Brightness temperatures are calculated from GOES IR pixel radiance counts using the standard IR calibration table (Clark, 1983).

The two assumptions made for this technique of determining cloud top heights are: 1) that a cloud is in local thermal equilibrium and has the same

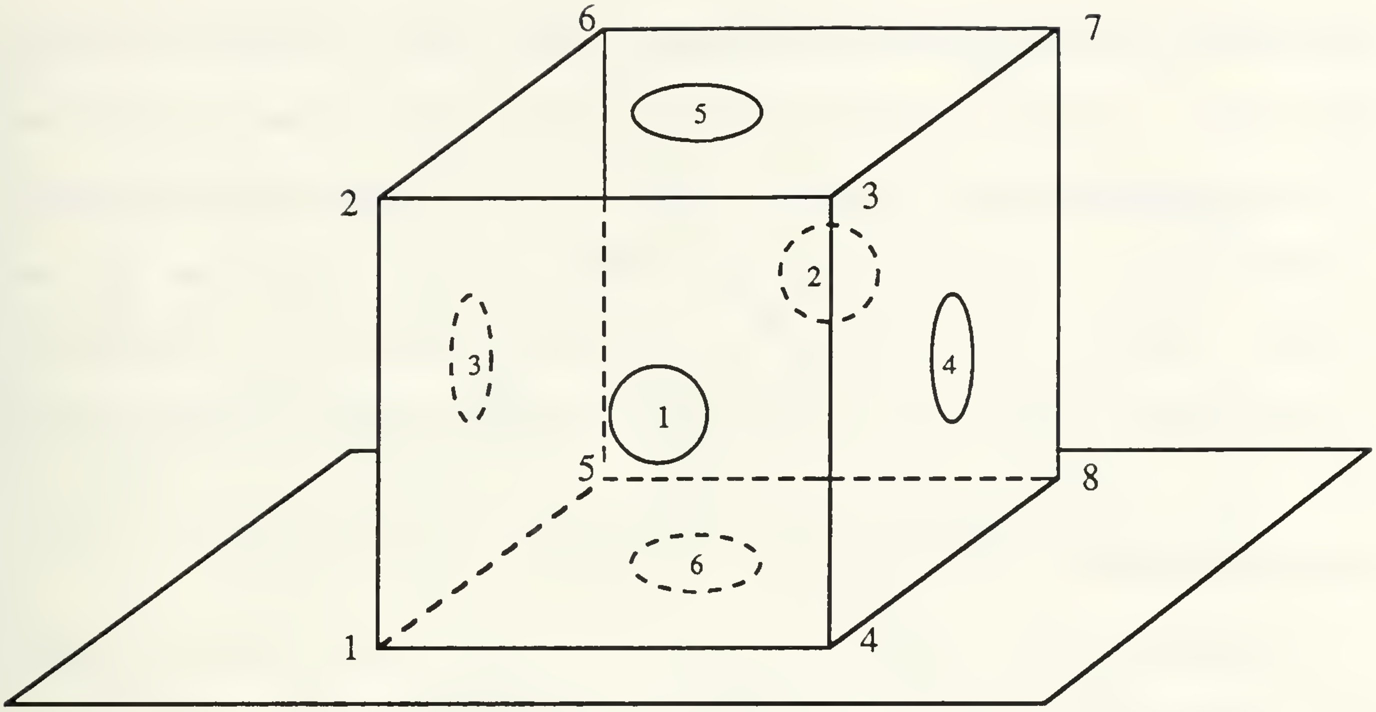


Fig 3a. Three-dimensional box suspended in space.

Coordinate #	Coordinate Array x	y	z
1	100	100	6
2	100	100	60
3	154	100	60
4	154	100	6
5	100	154	6
6	100	154	60
7	154	154	60
8	154	154	6

Part #	Nodes/Connectivity Array
1	1 2 3 -4
2	5 6 7 -8
3	1 2 6 -5
4	4 3 7 -8
5	2 6 7 -3
6	1 5 8 -4

Fig. 3b. Coordinate Array, Part Number and Nodes Array for the three-dimensional box in Fig. 3a.

temperature as the surrounding atmosphere, and 2) that a cloud is a perfect black body. If either of these assumptions are violated, then the estimated cloud top height will be incorrect. The first assumption should be accurate except in cases of extreme convection which can result in cloud tops that are warmer than their environment. The second assumption is significantly violated in the case of thin cirrus, because radiation from beneath the cirrus can pass through to the IR sensor and cause inaccurate brightness temperatures that are too warm.

Fig. 4 graphically illustrates the process of determining cloud top heights with sounding data from the Tampa Bay, FL radiosonde valid at 1200 UTC, 9 April 1984. From this particular sounding, all pixels with an IR brightness temperature of 288 K and 275 K are assigned heights of 1682 m and 3690 m, respectively. The program INTCLD (to be discussed) uses this procedure to determine cloud top heights for a combination of "smoothed" and unsmoothed pixels at all locations within a selected area of the IR image. The term smoothed refers to an average radiance count of more than one cloud pixel per grid point. Smoothing is necessary when areas selected for processing are larger than the resolution capabilities of the INTCLD program.

CLDGEN (to be discussed) uses the X, Y, Z coordinate points to determine the polygons and associated coordinate and nodes arrays for input to the MOVIE.BYU program DISPLAY. First CLDGEN locates all pixels that are connected and labels them as one cloud. Then the X, Y, Z coordinates of this cloud are analyzed for eleven combinations of pixel arrangements. These arrangements are used to decide which polygon combinations must be used to represent the cloud in three-dimensions. A sample of some pixel

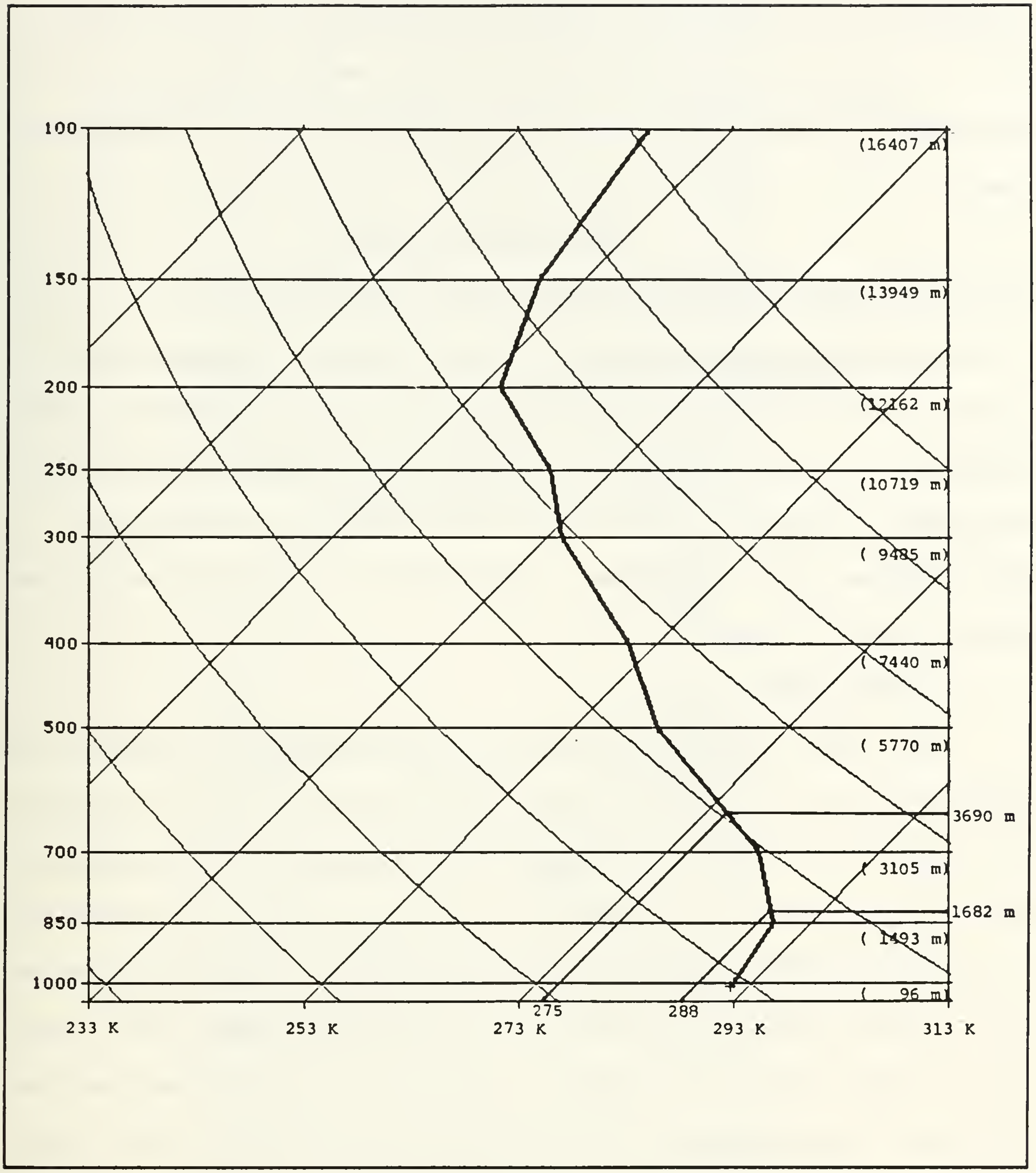


Fig. 4. Graphical illustration of determining cloud heights from IR brightness temperatures and sounding data. Sounding data is for Tampa Bay, FL 1200 UTC, 9 April 1984.

arrangements and corresponding polygon representations is shown in Fig. 5. Once the connectivity and nodes arrays have been created, these data are read into DISPLAY, and the cloud can be drawn from any location or orientation in space.

B. GENERATING GEOMETRY MODELS FROM SATELLITE DATA

As previously mentioned, there are several programs that must be run to create the cloud geometry models for input to the MOVIE.BYU program DISPLAY. This section explains the purpose of each program and demonstrates the process of going from satellite data to cloud models for one cloud scene. A full description of the modifications made to each of these programs for this thesis is given in Appendix A.1.

1. Program DEFSCT.

Fig. 6 shows the GOES IR and visible satellite images for a portion of the southeastern U.S. on 9 April 1984. Also shown in the boxed region of Fig. 6b is the portion of the scene, or subimage, to be modelled in three-dimensions. This selection process is accomplished by running the program called DEFSCT (Appendix A.2). The purpose of DEFSCT is to specify the area of interest and also to select a processing resolution. The processing resolution can be either 64 X 64, 128 X 128, or 256 X 256 screen pixels. This resolution determines how much pixel smoothing must be done on the area that is selected. For example, if the selected area of the IR image spans 256 X 256 pixels, and the processing resolution was selected to be 128 X 128, then a 2 X 2 smoothing is necessary to fit the data from the selected area into the program arrays. The selected data

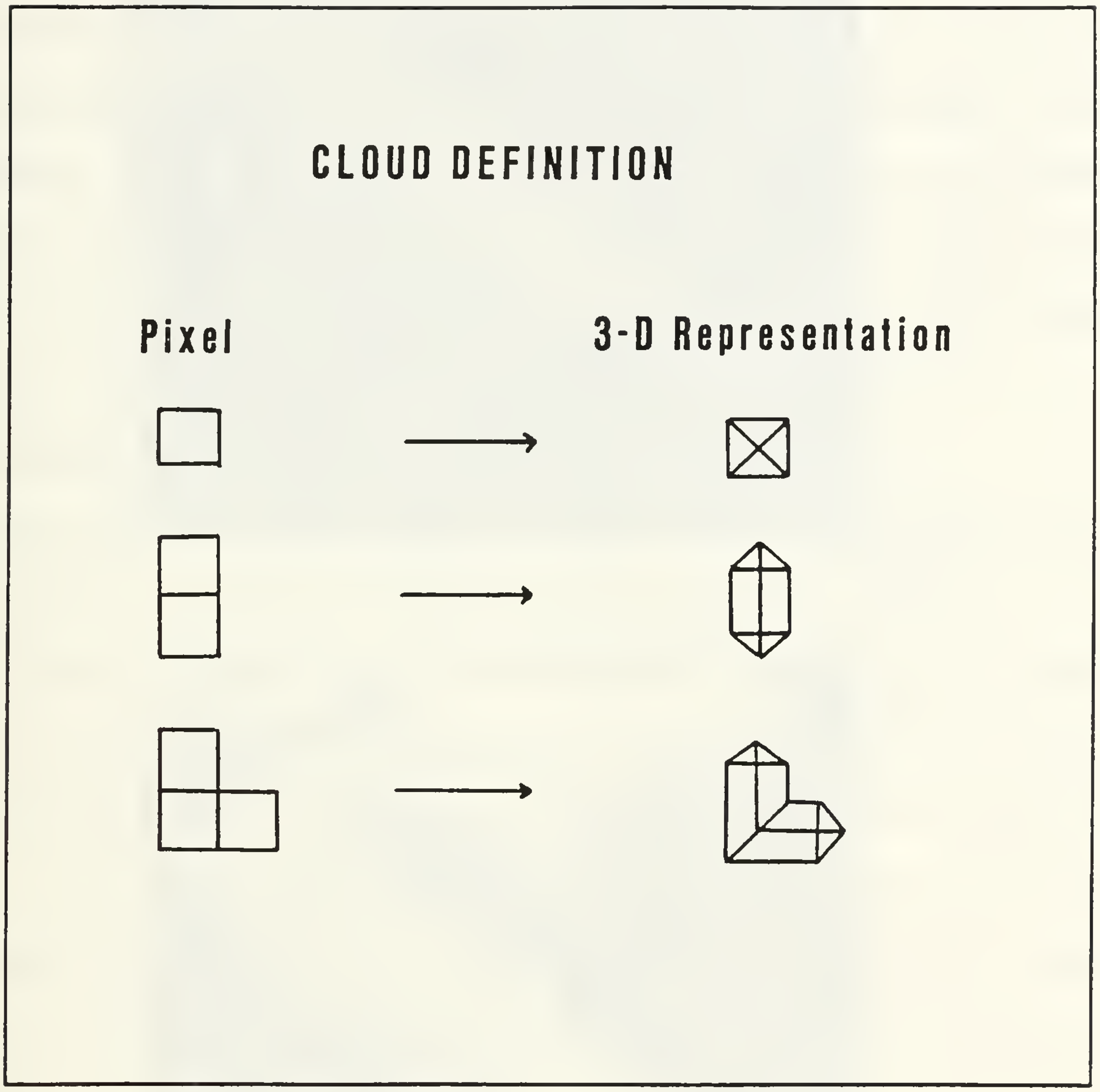


Fig. 5. Pixel arrangements and corresponding polygon representations (Meade, 1985).

(a)

(b)

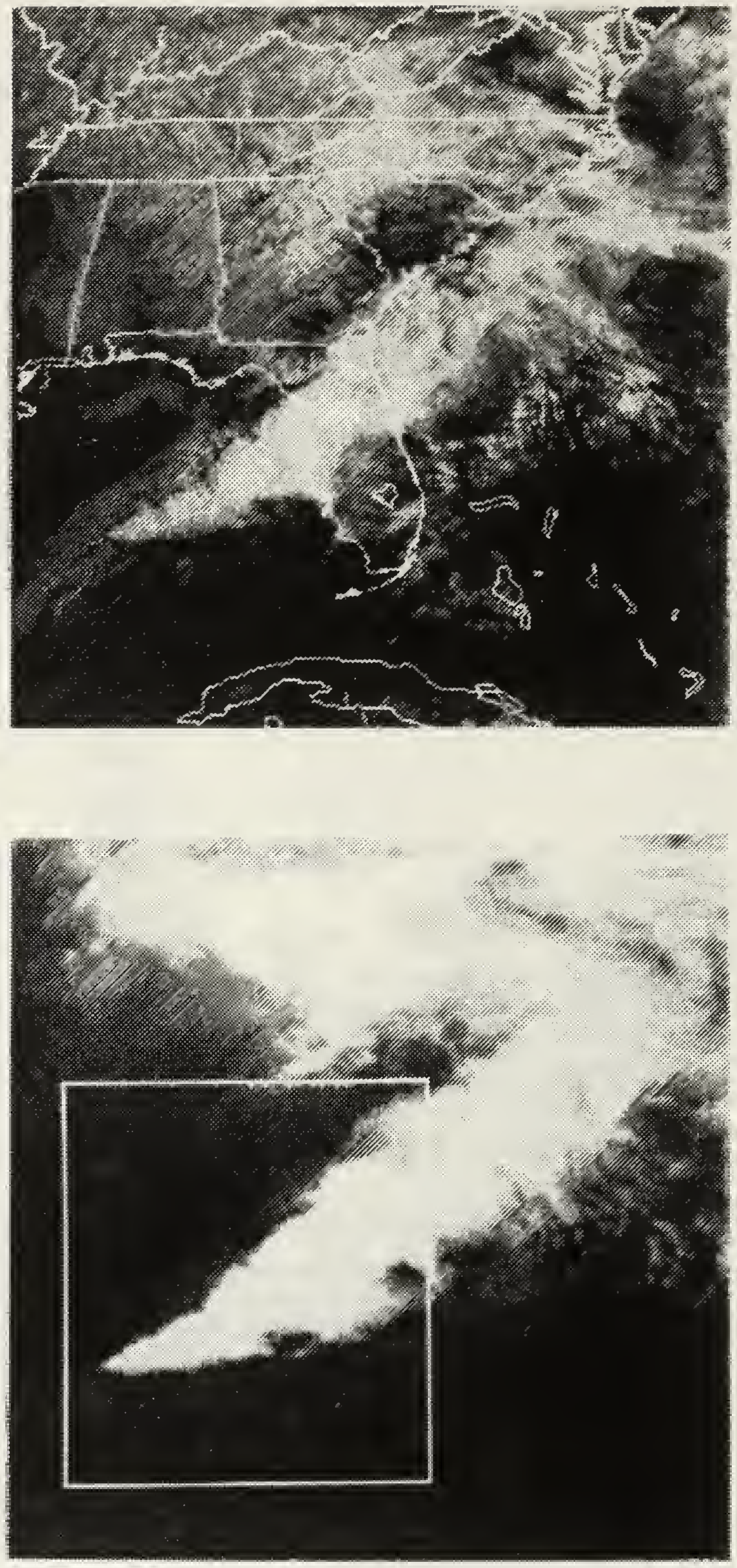


Fig. 6. GOES visible (a) and IR (b) subimages of the Southeastern U.S. for 1331 UTC, 9 April 1984. The boxed region of 6b will be modelled in three-dimensions.

refers to the IR radiance values or gray shades that make up the satellite image.

DEFSCT is an interactive program that prompts the user for file names and incorporates the use of a joystick for selecting the subimage of interest. Resolutions of 64 X 64 and 128 X 128 were used to create the three-dimensional images for this thesis. The final output from DEFSCT is a single file named DEFSCT.DAT. This file contains the file names and area definition parameters that define the selected subimage.

2. Program INTCLD.

The program INTCLD is run after DEFSCT is complete (Appendix A.3). This routine accomplishes the task of calculating the heights of all cloudy pixels within the selected satellite subimage. INTCLD first averages the satellite data according to the necessary smoothing scheme. The subimage selected in Fig. 6b is 256 X 256 pixels; therefore, every 2 X 2 pixel group must be averaged to one value so the data will fit into a 128 X 128 array. This process will inherently affect the resolution of the final three-dimensional image and limit which details of the original satellite picture are retained after smoothing.

Another important step, accomplished with the aid of INTCLD, is selection of an IR threshold value. The user is asked to input a value between 0 and 255. This value becomes the threshold, or cutoff, for which IR radiance values are considered to be cloud pixels. If the user selects a value of 0, all pixels are considered to be cloudy. This is unrealistic because land pixels have a varying range of IR values that must be filtered out of the final three-dimensional model. Usually a value between 80 (290 K) to 125 (268 K) works

well as a cutoff for cloudy versus non-cloudy pixels. However, this is an interactive selection procedure that must be accomplished for each cloud scene because land pixel values vary considerably based on the time of year and location of the image on the earth.

Fig. 7 illustrates the differences obtained by selecting two different IR thresholds. The pixels above the threshold of 84 (288 K) are shown in Fig. 7a, while those above the cutoff value of 110 (275 K) are shown in Fig. 7b. Notice how selecting a higher threshold value essentially filters out the lower, warmer clouds that surround the squall line. At 1200 UTC, 9 April 1984 a temperature of 288 K occurred at 1682 m on the Tampa Bay sounding (Fig. 4). So, by selecting a IR threshold of 84, all clouds tops below 1682 m are eliminated from the three-dimensional modelling process.

The user also must select a base height for the clouds while running INTCLD. Meade suggested using the LCL or some other value that can be graphically determined from sounding data. The original software only allowed one height to be input, and this value became the base for all the clouds in the final three-dimensional cloud models. For this thesis, the concept of using the LCL was expanded by creating an array that contains computer derived LCL's for evenly spaced grid points throughout the satellite image. Initial results are encouraging, and the processing requirements for this technique will be explained in the next chapter.

The end product of the INTCLD program is two arrays. One array contains the cloud top heights and the other contains the cloud base heights at each cloudy pixel location throughout the satellite subimage. As previously mentioned, cloud top heights are calculated by relating IR brightness

(a)

(b)

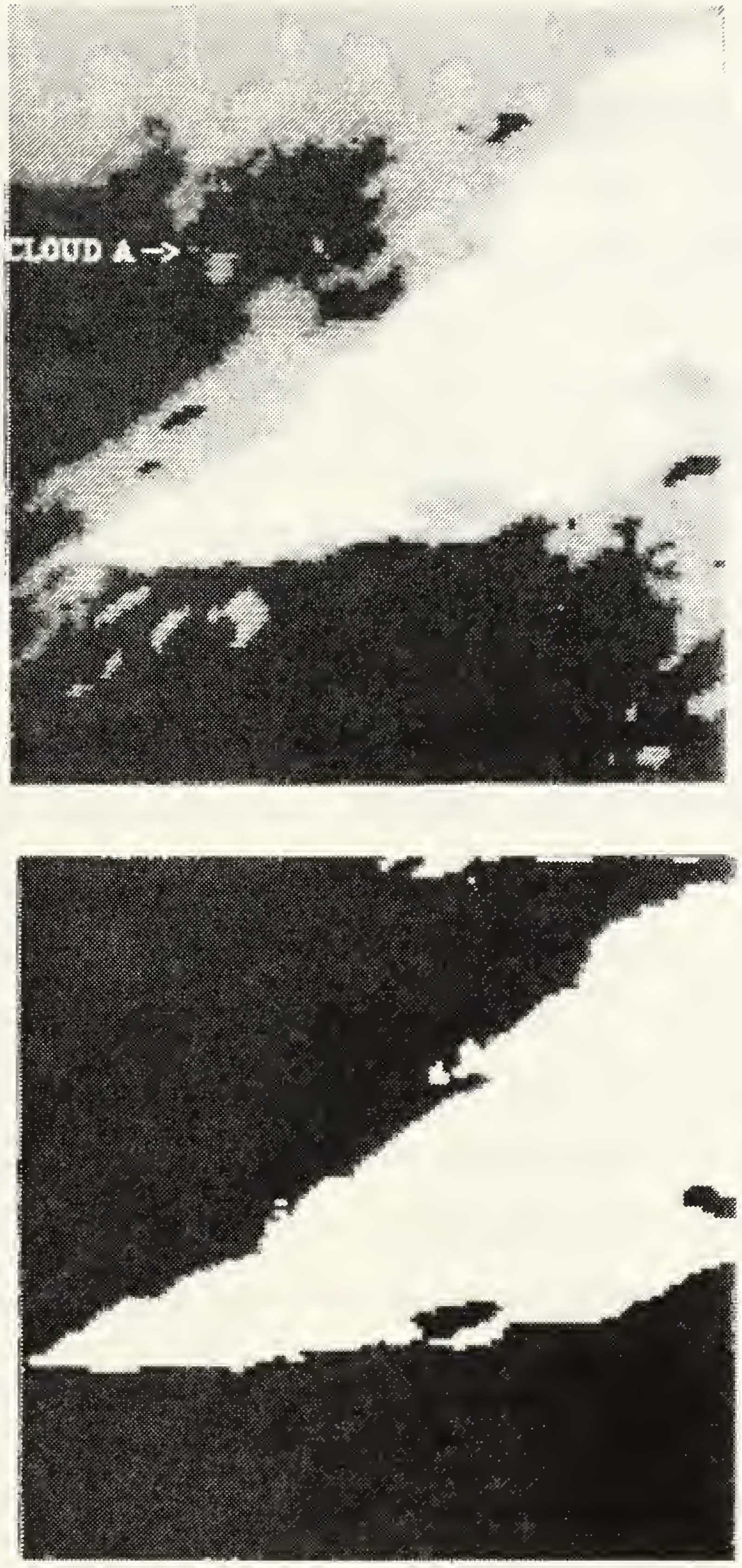


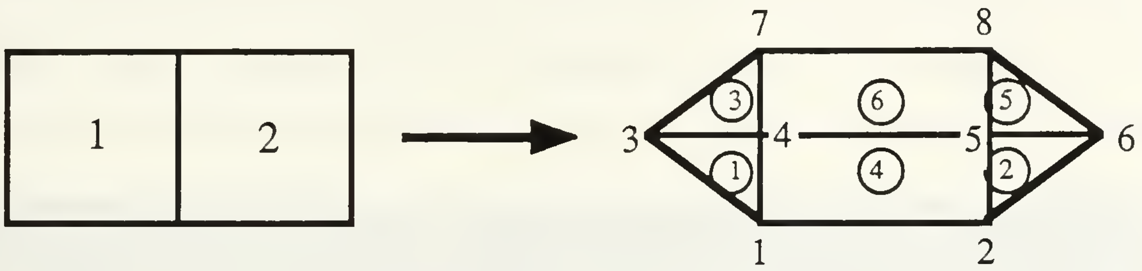
Fig. 7. IR cloud pixels above the thresholds of 84 (a) and 110 (b).

temperatures to the level on the sounding where the same temperature occurs. The height values for the cloud marked as Cloud A in Fig. 7a are shown in Fig. 8a.

3. Program CLDGEN.

CLDGEN must be run after INTCLD is complete (Appendix A.4). This program accesses the cloud base and cloud top height arrays and creates a geometry model for each cloud in the thresholded/smoothed IR subimage. The user has an option to change the scaling factor when CLDGEN is run. The scaling factor determines the vertical-to-horizontal aspect ratio of clouds to surface distance. The default value will cause clouds to be about four times higher in the vertical than in the horizontal. This scaling is necessary or else clouds will appear too flat, with little vertical variation, and very few details will be visible in the final three-dimensional image. However, when using this vertical scaling scheme, the three-dimensional clouds have a very realistic appearance. The causes of realistic vertically scaled clouds were demonstrated by Lovejoy and Schertzer, 1986. They proved that "clouds obey a fractal scaling law with similar shapes at different scales if the vertical-to-horizontal aspect ratio is adjusted to match the scale." The vertical scaling factors used to create the images for this thesis were between four to eight.

CLDGEN creates a cloud geometry model for every group of connected pixels that exist in the thresholded/smoothed IR subimage. Fig. 8 shows the data associated with the two pixels that connect to form Cloud A in Fig. 7a. Notice in Fig. 8a that these two pixels become a geometry model that consist of six polygons. The data that defines how to connect these polygons require eight X, Y, Z coordinates connected at eight nodes (Fig. 8b). CLDGEN stores the



PIXEL #:	IR RADIANCE	TEMP (K)	TOP HEIGHT (M)	BASE HEIGHT (M)
1	84	288	1682	915
2	84	288	1682	915

Fig. 8a. Pixel to polygon conversion for Cloud A. The height data for Cloud A is listed for reference.

Coordinate #	Coordinate Array x	y	z
1	112	338	3.75
2	116	338	3.75
3	110	340	3.75
4	112	340	6.87
5	116	340	6.87
6	118	340	3.75
7	112	342	3.75
8	116	342	3.75

Part #	Nodes/Connectivity Array
1	1 3 -4
2	2 5 -6
3	3 7 -4
4	5 2 1 -4
5	6 5 -8
6	8 5 4 -7

Fig. 8b. Coordinate Array, Part Number and Nodes Array for Cloud A. Note, the X, Y and Z values are in model unit coordinates.

data for each cloud in a separate file which has the format required by DISPLAY. Appendix A.4 gives an example of this file format. When CLDGEN is complete, the geometry model for each cloud is ready for input into the MOVIE.BYU program DISPLAY.

C. DISPLAYING CLOUD GEOMETRY MODELS

The program DISPLAY is used to create three-dimensional images, or pictures, of the cloud geometry models generated by CLDGEN. Appendix A.5 list the sequence of commands required to display the clouds above a blue surface as shown in Fig. 9. Cloud A is just one small cloud out of several that can be seen in this three-dimensional image. Two special graphics display options were used to create this image. These options were the shaded image option and dithering. The use of shading and dithering are mandatory to produce realistic cloud scenes.

By selecting the shaded image option in DISPLAY, clouds are shaded in with variations in color. This makes the clouds look solid and gives them a texture that simulates surface variations. When the shaded image option is not selected, clouds are drawn as wire diagrams. Dithering produces more variations in shade than the hardware actually provides. This is often done by half toning or patterning methods where varying amounts of black pixels are mixed with a certain number of colored pixels (Christiansen, *et al.*, 1987). When dithering is not used, connected polygons will abruptly change color and appear as distinct rectangles or squares in the three-dimensional image. Many additional graphics capabilities of the DISPLAY program were used to

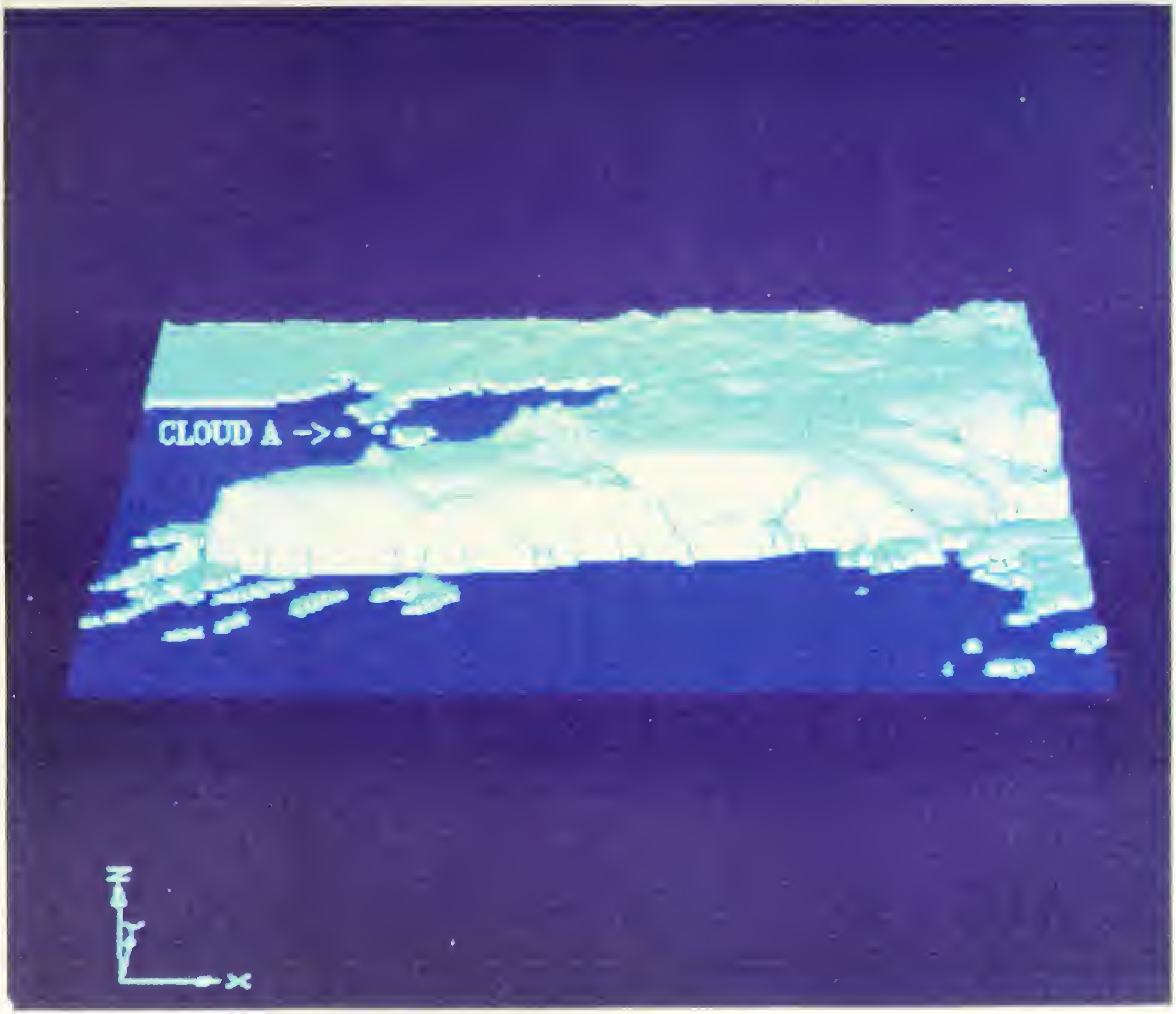


Fig. 9. Squall line clouds above a blue surface with the viewpoint from the south.

create the other images displayed in this thesis. These options will be referred to for each scene as applicable.

III. SATELLITE AND SYNOPTIC DATA

A. SATELLITE DATA

The satellite data used in this thesis consist of GOES IR and visible imagery showing a well developed squall line over the Gulf of Mexico and Florida on 9 April 1984. This squall line is part of a massive cyclone that stretched from the Great Lakes to the Gulf of Mexico (Fig. 10). The passage of this squall line through Florida was accompanied by several tornado sightings and one instance of severe hail (Svetz, 1985). The Space Shuttle Challenger mission 41-C also took several high resolution 100 mm photographs of this same squall line system. The time separation between the GOES IR/visible pair and the space shuttle photography was only three minutes (1335 UTC versus 1338 UTC, respectively).

The data were used as a case study because of the distinct vertical cloud patterns, and other excellent features for illustrating in three-dimensional displays. Additionally, the availability of closely time-spaced GOES imagery with space shuttle photography of the same squall line made it possible to subjectively compare details observable in the three-dimensional displays with high resolution images of the same features as seen from a similar vantage point of the space shuttle.

1. Subscene Selection

Subscenes of the squall line image had to be created before the software programs DEFSCT and INTCLD could access the satellite data. Full resolution was used for the IR subscenes, so these subscenes had a pixel resolution of

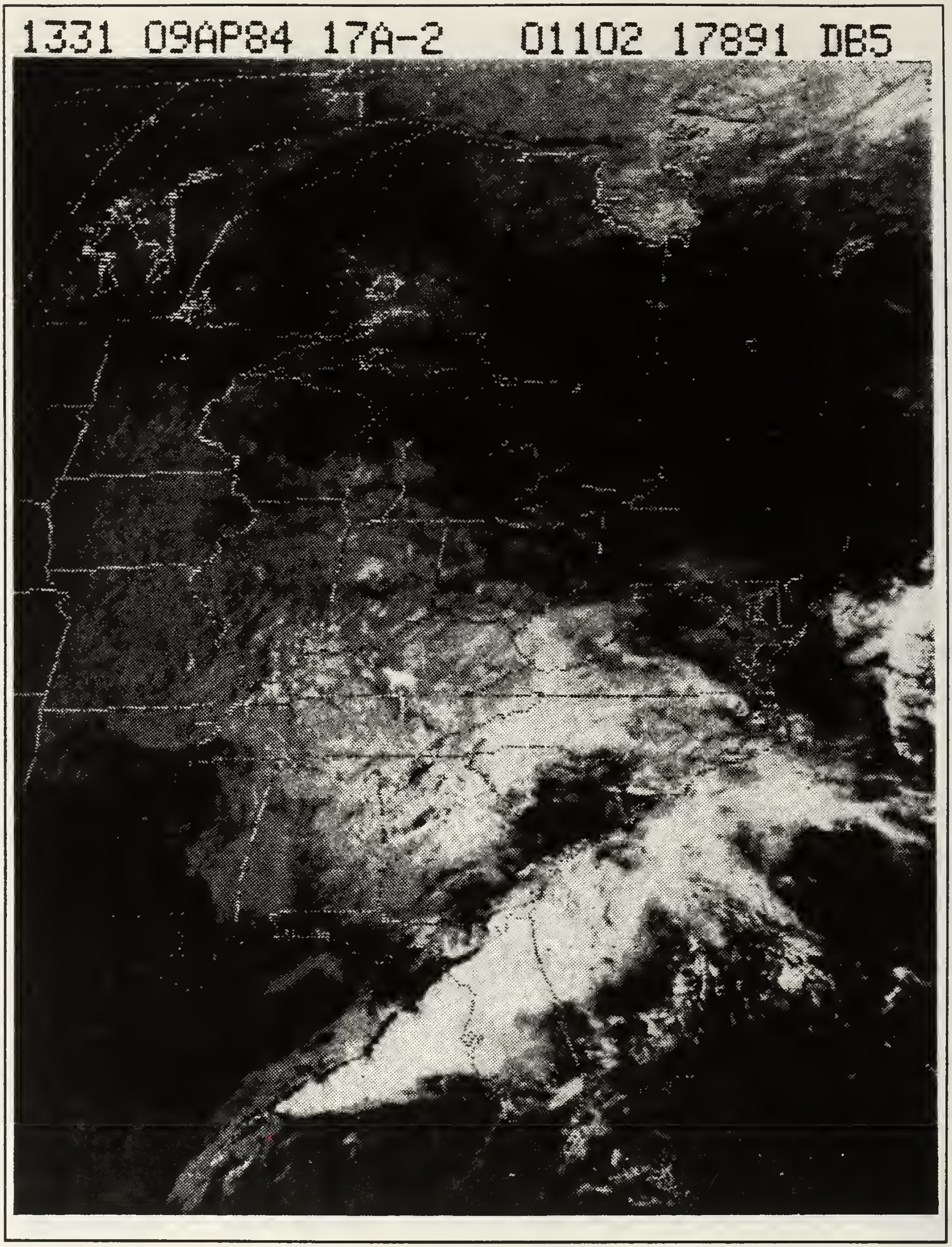


Fig 10. 1331 UTC GOES visible image of 9 April 1984 showing a massive cyclone over the southeastern U.S..

4 km in the X direction (east-west) by 8 km in the Y direction (north-south) (4 km X 8 km). GOES visible imagery has a normal resolution of 1 km X 1 km; therefore, only one of every four pixel values were used to create the visible subscene in Fig. 6a. The GOES imagery used for this case study was obtained from the University of Wisconsin.

The IR resolution of 4 km X 8 km caused an undesirable effect on the initial three-dimensional displays created from this satellite data. In Fig. 11a, notice the distinct cloud bands that run from east-to-west across this three-dimensional view of the squall line from the south. These bands are caused by the 8 km resolution of the IR imagery in the Y direction. Fig. 12a shows a small portion of the radiance values associated with the full resolution IR data for this squall line. Because of the 8 km resolution, there are always two consecutive rows of pixels with the same radiance values for any given column in the Y direction. The heights calculated for these pixels are identical, and this leads to very distinct changes in cloud heights at 8 km intervals in the north-south direction.

The banded patterns, seen in Fig. 11a, were not detected in previous three-dimensional displays created from GOES IR data. The reason such banded patterns were not noticed in the past was because the previous version of INTCLD was only capable of handling imagery pixel data in a 64 X 64 array. This meant that subimages 128 X 128 pixels or larger were averaged, or smoothed, to fit into the array. The averaging scheme essentially smoothed out the IR radiance values and removed the banded pattern from the IR data before the height values were computed in INTCLD. As a result, the banded patterns did not show up in the final three-dimensional displays even though

(a)

(b)

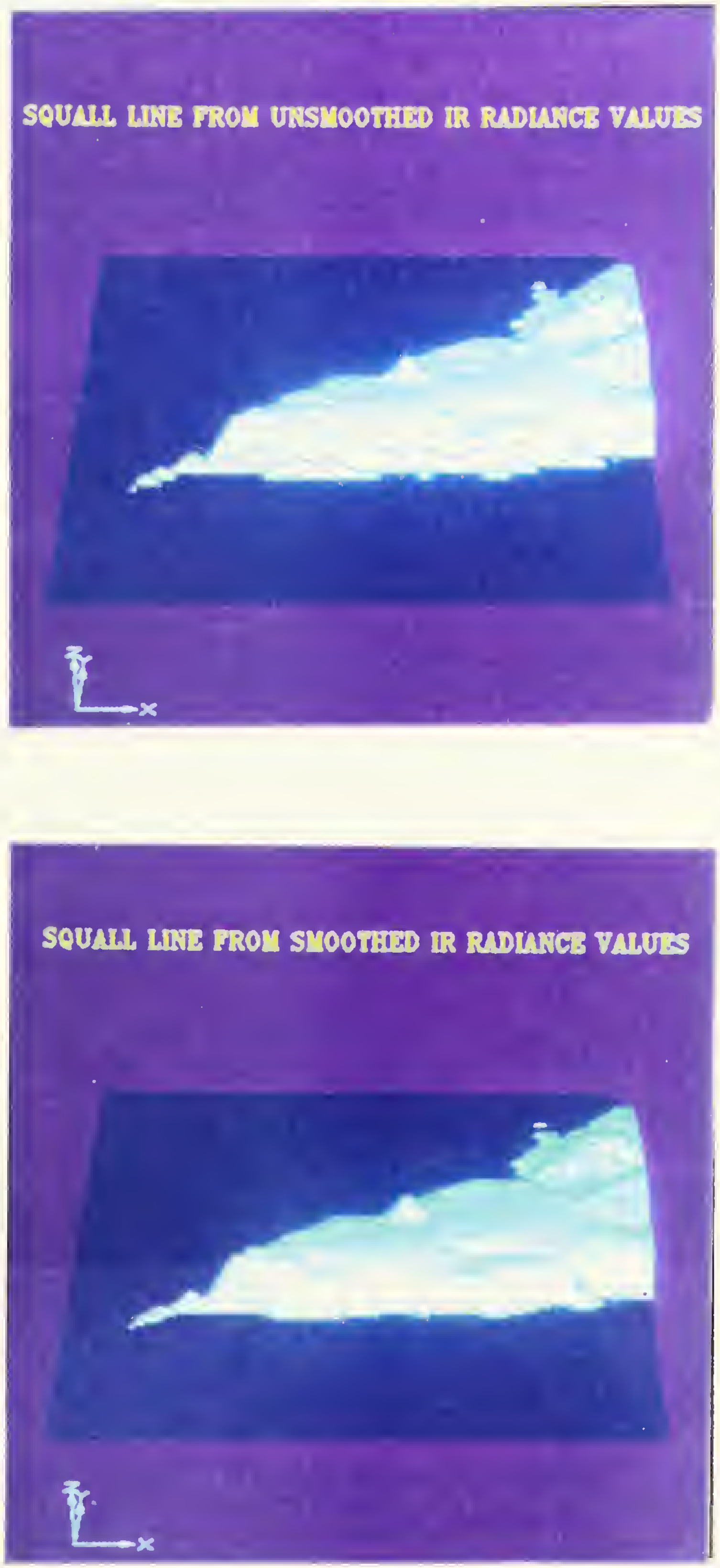


Fig. 11. View of squall line from the south showing results of unsmoothed (a) and smoothed (b) radiance values on the three-dimensional image.

4 km

93	97	98	101	99	98	98	97	97	95	95	95
100	103	104	104	103	103	101	100	101	103	104	104
100	103	104	104	103	103	101	100	101	103	104	104
102	102	102	102	104	104	105	112	127	145	159	167
102	102	102	102	104	104	105	112	127	145	159	167

8 km

Fig. 12a. Portion of unsmoothed radiance values for full resolution squall line IR subimage.

4 km

93	97	98	101	99	98	98	97	97	95	95	95
97	100	101	103	101	101	100	99	99	99	100	100
100	103	104	104	103	103	101	100	101	103	104	104
101	103	103	103	104	104	103	106	114	124	132	136
102	102	102	102	104	104	105	112	127	145	159	167

8 km

Fig. 12b. Portion of smoothed radiance values for full resolution squall line IR subimage.

they existed in the original data. The banded patterns depicted in Fig. 11a were only discovered after INTCLD was modified to handle data from 128 X 128 or 256 X 256 subimages in full resolution.

From considerations of visual realism, it was necessary to remove this banded pattern from any full resolution three-dimensional displays of satellite data. These bands were removed by applying a simple "odd pixel" smoothing scheme to the original full resolution IR radiance values. This odd pixel smoothing scheme is illustrated in Fig. 12b. The first row of radiance values were left unchanged. Then every even row of radiance values became the average of the two odd radiance row values surrounding that even row at matching column locations. The final result was an IR image that looked the same as the original image but had smoother variations of radiance values in the Y direction. After the banded pattern was averaged out of the IR data, the three-dimensional clouds created from this smoothed data had a more realistic appearance (Fig. 11b).

2. Satellite Navigation

The GOES IR and visible subscenes were navigated to create latitude and longitude (lat/lon) files corresponding to the earth location of this satellite image pair. These lat/lon files were used by the GEMPAK[1] routines that draw maps of geopolitical boundaries over the satellite imagery. It was also essential to know the lat/lon coordinates of the southwest (SW) and northeast (NE) corner points of this satellite subscene. The corner points were used as boundaries for the GEMPAK routines that produced objective analyses (OA) of

[1]GEMPAK routines were developed at the NASA/GSFC (desJardins and Petersen, 1986). These routines are described in Section 3.B.1.

grid point data of the pressure, potential temperature and LCL values used in this thesis.

B. SYNOPTIC DATA

Three thermodynamic parameters were chosen to illustrate the potential usefulness of displaying atmospheric synoptic data in three-dimensions. The parameters chosen were pressure, potential temperature and the LCL. Pressure was picked because this parameter is commonly used by meteorologist to determine the state of the atmosphere. Potential temperature was used to illustrate some atmospheric dynamic concepts including locating the tropopause and thermal wind structure from the temperature gradient. The LCL was incorporated into the display of clouds as a "first guess" for determining the cloud base heights throughout the region of interest.

Objective analyses of pressure, potential temperature and LCL temperature were generated from the 1200 UTC, 9 April 1984 sounding data. The pressure and potential temperature values were transformed into three-dimensional geometry models by the routine CLDGEN and displayed along with the cloud geometry models of the squall line. The LCL heights were computed as an option within the program INTCLD. These heights were computed with the same algorithm used to determine cloud top heights. However, the cloud base heights were determined from an objective analysis array of LCL temperature values versus the IR brightness temperature values used to calculate cloud top heights. The sounding data used for this thesis were obtained from the National Climate Data Center (NCDC), Asheville historical data tapes, and the procedure for decoding these tapes into GEMPAK format is explained in

Appendix B.1. This section explains the additional data processing required to create the displays of atmospheric synoptic data used in this thesis.

1. GEMPAK Routines

GEMPAK is a General Meteorological Software Package developed at NASA/GSFC to support the mesoscale research program. The system includes programs for displaying, analyzing and integrating meteorological data. Displays can be made of information such as geopolitical boundaries, station soundings, weather maps and cross sectional analyses for any area of the earth where data are available. GEMPAK also has routines that perform Barnes objective analyses of meteorological data, plot contours and streamlines, and compute meteorological diagnostic results. (desJardins and Petersen, 1986). The GEMPAK routines were used extensively to create the three-dimensional displays of synoptic data in this thesis.

The objective analysis capability of GEMPAK was used to generate arrays of height data for selected levels of pressure and potential temperature. These height arrays contain a set of evenly spaced data that corresponds to the area of the earth being viewed in the IR/visible squall line imagery. The objective analysis routine also was used to generate an array of LCL temperature values for the same region of interest. Unfortunately, GEMPAK does not have the capability to calculate the height of the LCL; therefore, the data for LCL values had to be handled differently than the pressure and potential temperature information. The GEMPAK software also was used for several other purposes. As previously mentioned, the capability of plotting geopolitical boundaries over satellite data was used to determine the accuracy of the lat/lon files.

GEMPAK routines were also used to modify the GEMPAK sounding data file created from the NCDC sounding data.

The sounding data were modified to incorporate National Meteorological Center (NMC) grid point values of temperature and height data for the area of the imagery that was over water. This was necessary because GEMPAK's objective analysis routine did not produce any values for a large number of the grids over the Gulf of Mexico and the North Atlantic Ocean. CLDGEN does not have the logic to handle missing data; therefore, the sounding file was modified with the NMC grid point data for 22 lat/lon locations over water. These additional grid point values essentially "filled-in" the missing data in the GEMPAK sounding file. Fig. 13 is a GEMPAK produced map that shows the locations where additional NMC sounding data were used. Also shown in this figure is the boundary of the satellite subimage in relation to geopolitical boundaries, and the locations where regular sounding data were available.

2. <u>3D_LAYER</u>

The program 3D_LAYER was written to convert an array of objective analysis height values into a format acceptable by the routine CLDGEN. The CLDGEN routine was previously explained in Section 2.B.3. Since CLDGEN simply works with two arrays, one for the model's bottom and one for the model's top, this same program was used to generate the three-dimensional models of the pressure and potential temperature surfaces. The purpose of 3D_LAYER is to create two arrays of height values that define the bottom and top of the surface of interest. Each surface is treated as an infinitesimally thin layer, so the arrays contain the same height values. The main processing accomplished within 3D_LAYER involves linearly interpolating the smaller

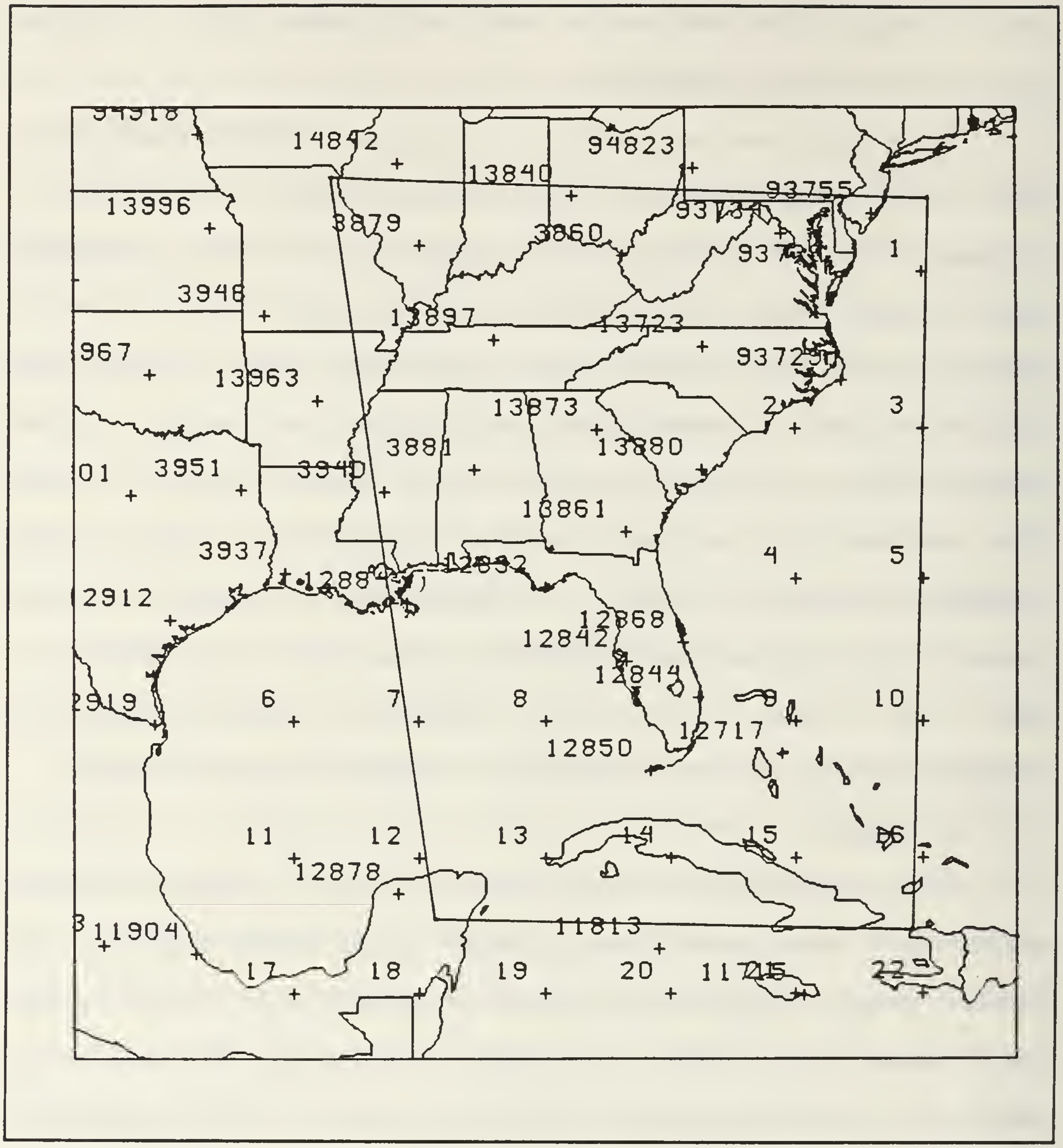


Fig. 13. Satellite boundary, regular sounding stations and the 22 locations where NMC data were used to supplement the available sounding data.

GEMPAK array of objective analysis grid values to a 512 X 512 array of grid values that overlay the original satellite subimage. These interpolated height values are written to files for access by CLDGEN. Appendix B.2 gives a full explanation for generating three-dimensional models from the objective analysis height values of pressure and potential temperature data.

IV. THREE-DIMENSIONAL IMAGERY

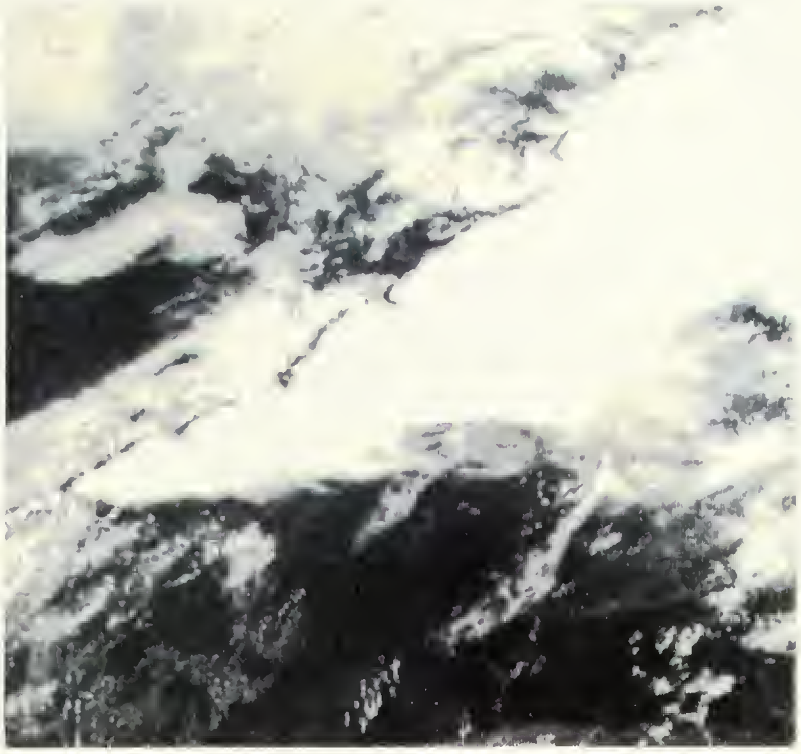
This chapter presents possible uses of displaying clouds and synoptic weather data in three-dimensions to interpret the structure of the atmosphere. First, a comparison is made between an overhead 3-D cloud scene to the same cloud scene in the visible satellite image. Then, the vertical structure of the squall line is analyzed using three displays: an enhanced IR image, a side view of clouds in three-dimensions and a high resolution space shuttle photograph.

Also, the results of displaying clouds and surfaces are presented in this chapter. The three types of surfaces displayed are: constant height levels, pressure level surfaces and potential temperature surfaces. Applications for these types of cloud and surface displays will be discussed as each display is presented. Finally, the results of using LCL values to determine cloud base heights is presented in the last section of this chapter.

A. COMPARISONS

A comparison was made between satellite imagery and an overhead three-dimensional view of the same region. This comparison illustrates the capabilities of representing the general structure of individual clouds and synoptic storm systems with the graphical display technique used in this thesis. These results are depicted in Fig. 14 which shows two views of the squall line. The first view, Fig. 14a, is an enlargement of the visible satellite image that corresponds to the IR subimage shown in Fig. 7a. The second view,

(a)



(b)

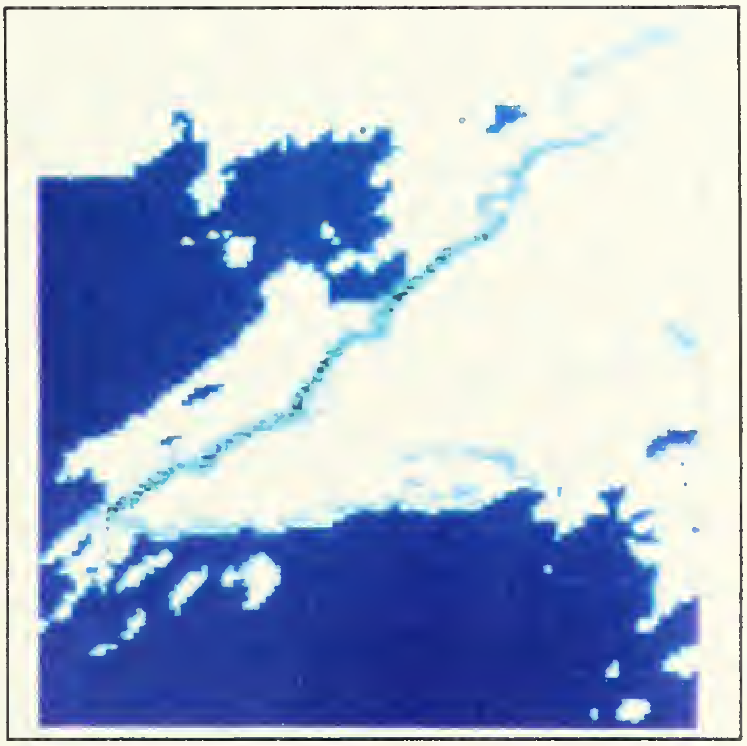


Fig. 14. Two views of the squall line. Enlarged visible image (a) and graphically generated view of the same region (b).

Fig. 14b, shows a graphically generated view of the same region. Fig. 14b was created with a 2 X 2 pixel smoothing over a 256 X 256 subimage which gives these clouds an 8 km resolution. An IR threshold of 84 (288 K) was selected for the clouds in this figure; therefore, not all of the clouds seen in the visible image are retained in this overhead three-dimensional graphics view. Shading was added to Fig. 14b by simulating shadows cast from a light source at the location of the sun (See Appendix C).

The addition of shadows to the three-dimensional view of the squall line allows one to compare the visible and graphically generated images for similarities. Notice the distinct back edge of the squall line is highlighted by dark shadows in both images. This dark edge occurs because shadows from the higher convective clouds are cast down on the lower stratus cloud deck beneath the squall line's back edge. The shading in this figure also facilitates a comparison of the graphically generated image to the visible image. These two views of the squall line have a very similar appearance considering the 8 km resolution and IR threshold that eliminated some of the warmer, lower cloud groups. The use of shadows also can be helpful for determining the location of convective turrets and will be discussed below.

One advantage of this three-dimensional graphics technique is that shadow scenes can be produced for any image regardless of the time of day. This feature could be useful for analyzing nighttime IR imagery. By creating a three-dimensional view from an IR image, and using a simulated low sun angle to produce shadows, the vertical structure of clouds would be "visible" to forecasters for use in interpreting the satellite image.

A technique used to analyze IR imagery for cloud structure involves using an enhancement scheme that highlights cloud top temperatures with varying gray shades or color. An enhancement scheme routinely used for GOES IR imagery is the MB enhancement (Clark, 1983). Cloud heights are directly related to their temperature, so this enhancement is useful for determining the vertical structure of clouds. Fig. 15a shows the MB enhancement applied to the IR image area of Fig. 14a. The sharp edge of the squall line shows up as a region of dark gray clouds with very distinct temperature gradients in this enhanced IR image. The lower clouds, around the squall line, are either white or gray indicating their warmer temperatures. There are three distinct areas of bright white clouds near the left center of Fig. 15a. These are regions of very cold cloud tops with temperatures below 215 K. Svetz (1985), using information from the enhanced IR imagery at 1331 UTC and the Tampa Bay, FL sounding, estimated the coldest cloud tops in this squall line were near 12,800 m. This height was close to the 13,415 m height measured by the Tampa Bay, FL radar of the highest cloud tops at 1340 UTC.

The enhanced IR image is very useful for determining the general vertical structure of clouds. However, forecasters must still manually determine cloud heights by relating IR temperatures to sounding profiles. This can be a time consuming process and requires a certain amount of experience. Also, the MB enhancement only gives a range of temperatures for each gray shade. This temperature range varies between 4 K to 10 K which can contribute to an error of up to 1,000 m in cloud top heights.

Another view of this cloud scene was produced to show how shadows can greatly enhance the three-dimensionality of an image. Fig. 15b shows the

(a)

(b)

Fig. 15. 'MB' enhanced IR subscene (a), and the squall line from the south with shadows added to the three-dimensional image.

squall line from the south with a 60° rotation about the original X–axis. The simulated sun is at a lower angle above the horizon in this view which causes very elongated shadows on the northwest side of each cloud. Of particular interest are the two convective turrets (cumulonimbus tops) that clearly stand out with the addition of shadows. Both turrets are along the back, northwest edge of the squall line, with one in the center of the image and the other towards the upper right corner.

This three-dimensional image, combined with shadows, indicates the turret in the upper right corner is much broader than the smaller turret near the center of Fig. 15b. The shape of this turret corresponds well to this same feature in the enhanced IR image. The broader turret was also distinctly visible in each of the space shuttle photographs taken of the squall line. Fig. 16 is a space shuttle photograph taken at 1338 UTC. The broad turret clearly stands out as the tallest mass of clouds along the edge of the squall line. In the shuttle photography, as observed by Scanlon (1987), shadows highlight the structure of turrets and "gave them more of a three-dimensionalimpression since the oblique sun angle provided ideal shadows that outlined the circular, stepwise intrusions the thunderstorms made into the tropopause."

An interesting feature of Fig. 15b is that the height of the two turrets are about the same. This is not apparent in the space shuttle photograph (Fig. 16) and is only hinted at in the enhanced IR image as a region of colder IR temperatures (Fig. 15a). However, the convection associated with this turret is suggested at its location as indicated by the "notched" pattern in the clouds. This notch is located to the southwest of the turret and is probably formed by

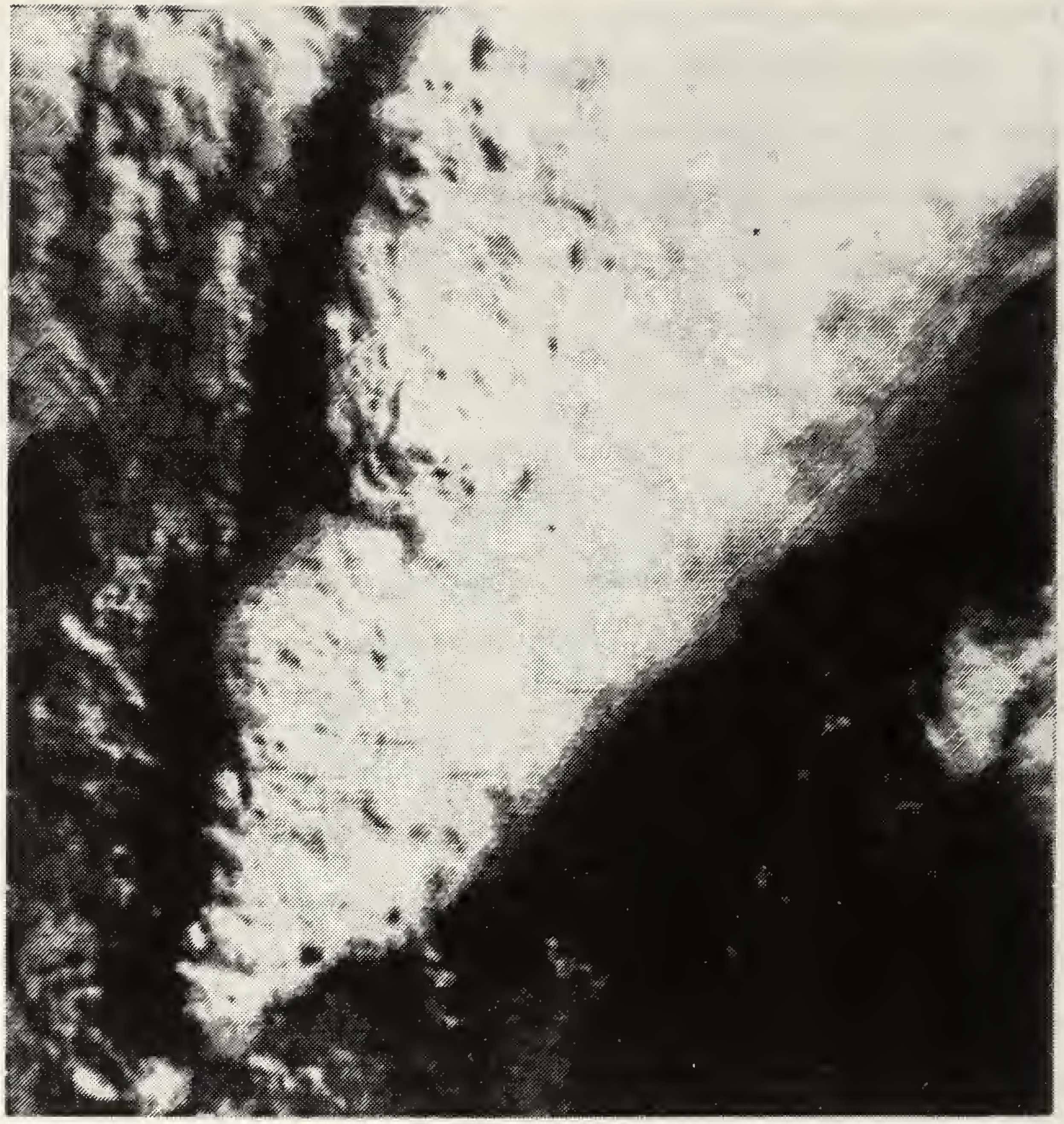


Fig. 16. View of the squall line from the Space Shuttle Challenger. Orbit 47, 1338 UTC, 9 April 1984.

induced subsidence around the deep convection (Scanlon, 1987). It is also possible that the smaller turret was not quite as tall at the time space shuttle photograph was taken; because during extreme convection, thunderstorms can rapidly change in size and shape.

Convective turrets, such as the two embedded in this squall line, are often associated with extreme convection and can be used as an indicator of storm intensity. However, Scofield and Purdom, 1986 state that:

> there is one serious limitation in using overshooting tops (convective turrets) as storm intensity indicators: they are detectable for only a few hours in the early morning or late afternoon when the sun is low enough on the horizon for the tops to cast shadows on the underlying anvil.

But, by using the simulated light source capability of the MOVIE.BYU display software, any high resolution three-dimensional cloud scene could be analyzed for convective turrets; thus, three-dimensional imagery could be a possible aid to severe weather forecasters. It is important to note here that only high resolution displays (4 km or less) could consistently be used for this type of forecasting. This is necessary because many severe weather events occur at the mesoscale where the signatures of severe weather, such as a tornado vortex or overshooting dome cloud, may only be 1 to 5 km in horizontal extent (Fujita, 1986).

Figs. 14b and 15b demonstrate that shadows are very useful for highlighting the vertical structure and details of graphically generated three-dimensional cloud imagery. Even with the 8 km resolution of the clouds in Fig. 14b, the general structure of the visible cloud patterns are highlighted in the overhead three-dimensional view. Additionally, the shadows cast onto the lower cloud decks highlight the very distinct edge of the squall line. Also, the size and shapes of convective turrets are easily picked out in the three-

dimensional view (Fig. 15b) when the cloud scene is viewed at an oblique angle and shadows are added to give extra detail to the image.

B. CLOUDS AND SURFACES

1. Clouds and Height Levels

A display combining clouds and constant height levels is useful for showing the vertical depth of clouds. Fig. 17 demonstrates this technique of displaying clouds and height levels. This figure shows the same clouds seen in Fig. 13b along with three constant height levels at the surface, 915 m (3,000 ft) and 9,150 m (30,000 ft). The viewpoint is from the north, and squall line shows up as a mountain of clouds with tops completely above 9,150 m, running through the center of this figure from the northeast to the southwest.

Displaying clouds and height levels could be a useful briefing aid for forecasters that brief pilots. For example, consider briefing a pilot on a proposed flight plan from Apalachicola, FL to Tampa Bay, FL during the time this squall line is moving across the Gulf of Mexico. For reference, Apalachicola is station no. 12832 (northwest Florida) and Tampa Bay is station no. 12842 (west central Florida) in Fig. 13; the squall line was located between these two cities at 1331 UTC, 9 April 1984 (Fig. 6a). The forecaster could explain how this cloud system is well organized with the only break in the clouds below 30,000 ft occurring in the northeast where the squall line passes over Florida. The pilot would quickly realize that his flight path would have to be to the east, over land, or a southern route that circumvents the tip of the squall line and approaches Tampa Bay, FL from the south. The capability to brief

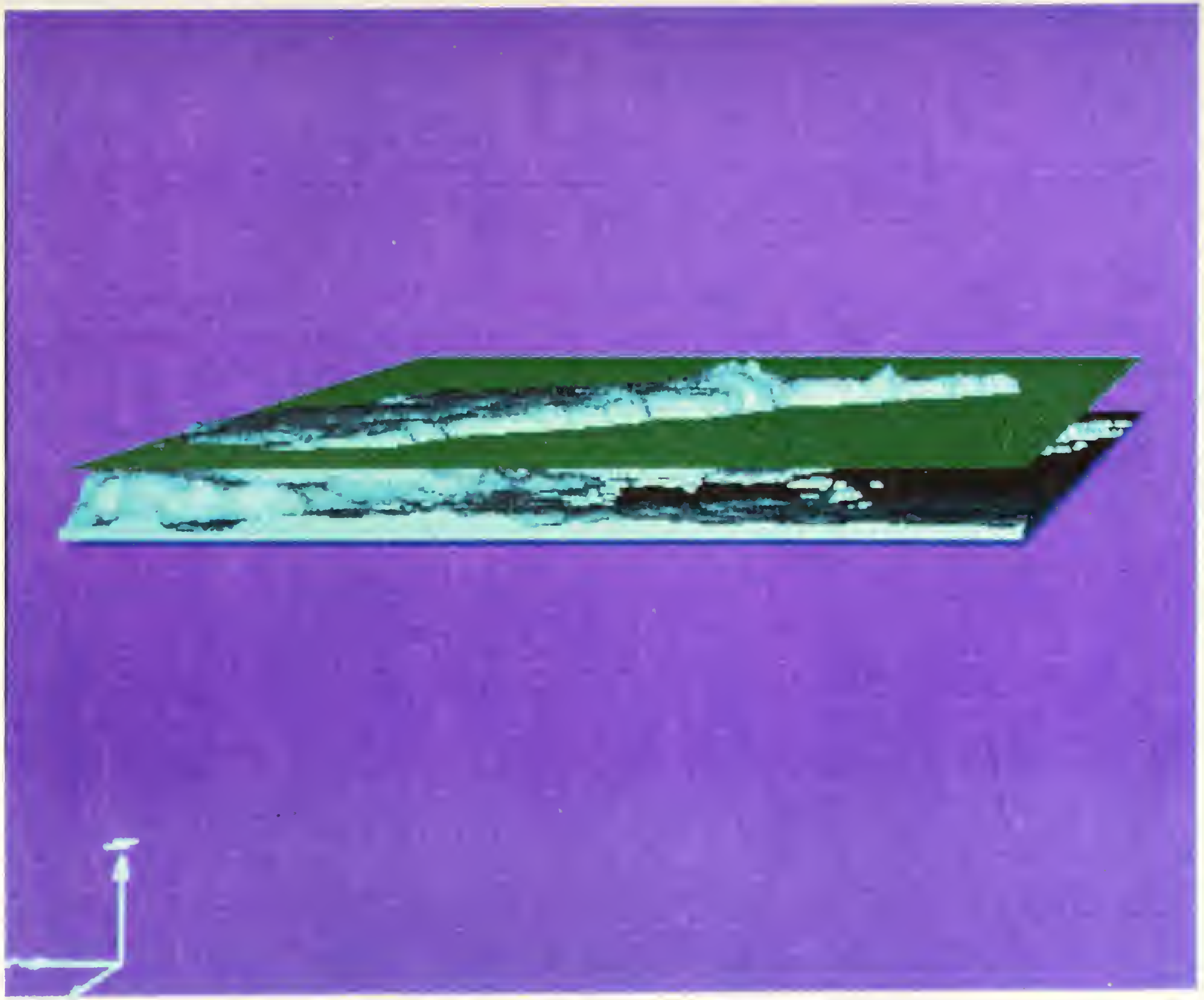


Fig. 17. Squall line from the north with three constant height levels: the surface (blue) 915 m (red) and 9,150 m (green).

pilots, by incorporating a 3-D flight track within a cloud and topography model, was originally demonstrated at CSU (Vonder Haar, *et al.*, 1988).

2. Clouds and Pressure Surfaces

Several three-dimensional views of the entire satellite image were created with pressure surfaces added to the display. Fig. 18 shows one of these images that includes the 850 mb (red), 700 mb (green), 500 mb (blue) and 300 mb (red) pressure surfaces along with clouds. The viewpoint of this figure is from the east, so the squall line is the main group of clouds above the 300 mb surface on the left, southern side of the image. An IR threshold of 110 (275 K) was selected as a threshold for the clouds in Fig. 18. Also, a flat cloud base of 3,050 m was used; therefore, all the low clouds below 3,050 m are not visible in this figure.

The clouds in Fig. 18 were created with an 8 X 8 pixel smoothing over the entire 512 X 512 satellite image which gives these clouds a 32 km resolution and effectively removes any small scale details. The resulting three-dimensional image does not have the high resolution and smooth clouds as seen in previous figures. The low resolution was necessary to keep the total number of polygons for the combined cloud and pressure geometry models below the current limit of 25,000 polygons.

The larger number of polygons, or finite elements (FEs), are required because the modelling process, accomplished in CLDGEN, uses several FEs to model the vertical variations of pressure heights for each X and Y point in the subimage. Whereas clouds generally cover less than 50% of the subimage, pressure height values cover 100% of the subimage at every X and Y point (or pixel location) in the display. As a result, the number of FEs drastically

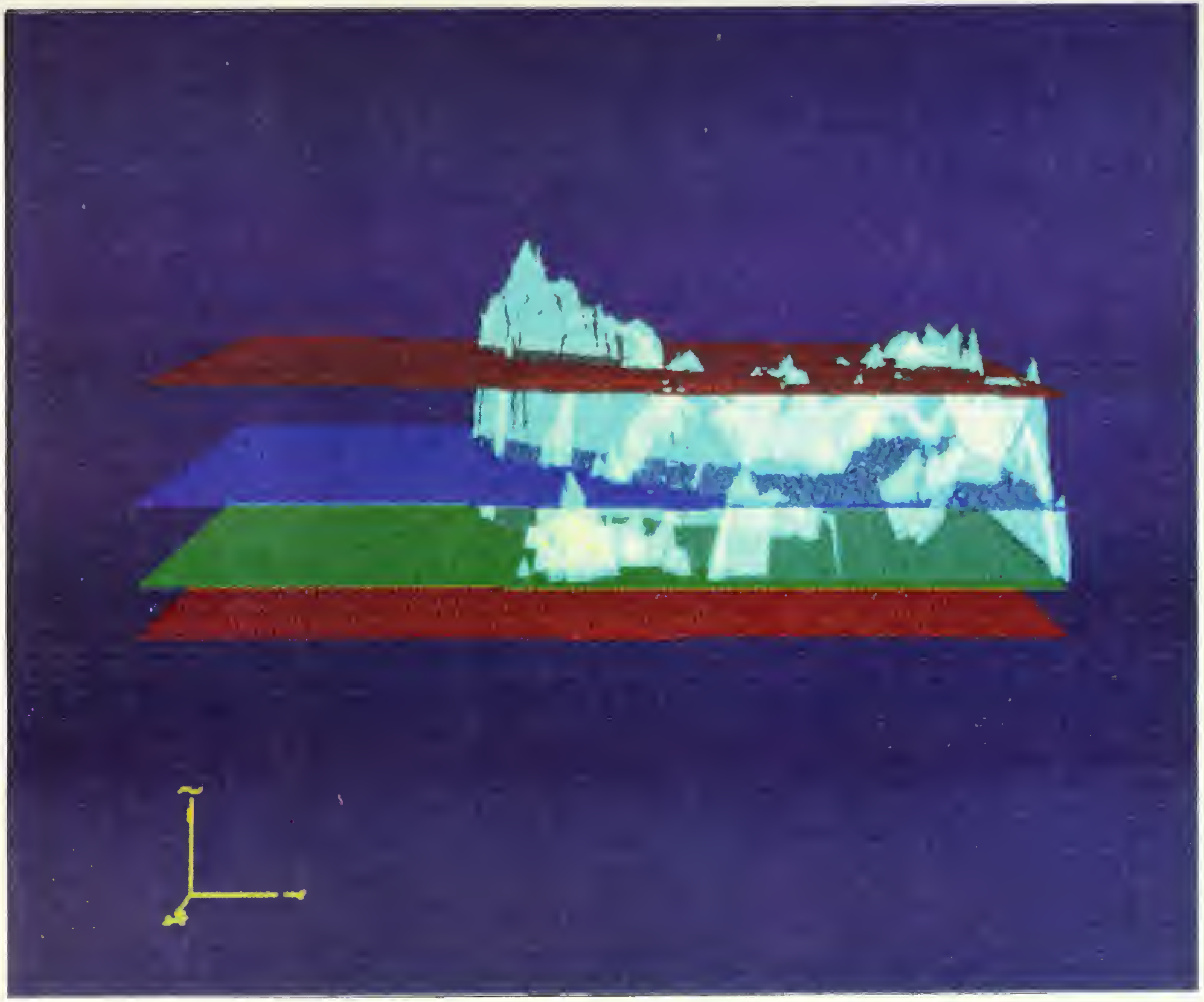


Fig. 18. Three-dimensional view of entire satellite image from the east with four pressure surfaces: 850 mb (red), 700 mb (green), 500 mb (blue) and 300 mb (red).

increases for each additional pressure surface added to the display. This resolution restriction also applies to the displays of clouds and potential temperature.

Even with its low resolution, Fig. 18 nicely illustrates the concept of displaying clouds and pressure surfaces in three-dimensions. One can see a large portion of the cloud tops protrude above the 300 mb surface[2] which has an average height of 9,400 m. The pressure surfaces are relatively flat, with the greatest slope occurring over the 300 mb surface which varies from 9,170 m in the north to 9,650 m in the south of this image. The 480 m variation of the 300 mb surface is barely detectable even with a vertical-to-horizontal scaling factor of 8-to-1. The average north-south variation of the three other surfaces is only 210 m. This is essentially imperceptible because the north-south distance covered by this subimage is over 1,300 km giving these surfaces a slope of less than 2.5/1000.

None of the meteorological relationships such as the geostrophic wind, or location of low and high centers can be seen with this technique of displaying pressure surfaces. To highlight the slopes of pressure surfaces would require using a vertical-to-horizontal scaling ratio too large for meaningful, realistic cloud-pressure displays. A display of only pressure surfaces with a very high vertical scaling factor could be used to illustrate the vertical relationships between pressure surfaces at different levels. This exaggerated scaling factor might also bring out the local variations of height and make it possible to see the high and low pressure center locations.

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[2] The clouds is the north of Fig. 18 are taller than their true height. This discrepancy is explained in Section 5.B.1.

3. Clouds and Potential Temperature Surfaces

Potential temperature surfaces are used to study the dynamics of the atmosphere and they have considerably more slope than pressure surfaces. For this reason, three-dimensional displays of clouds and potential temperature surfaces should be extremely useful forecasting and briefing aids. A short review of potential temperature concepts is given before illustrating three-dimensional displays of clouds and potential temperature surfaces.

One indicator of fronts is a strong gradient of potential temperature. Fig. 19 is a cross-sectional analysis of potential temperature between Omaha, NE (OMA) and Veracruz, Mexico (VER) for the sounding data of 0000 UTC, 8 April 1984. This figure also shows the location of a westerly jet core associated with these potential temperature surfaces. In Fig. 19, the strongest temperature gradient at the surface occurs between Stephenville, TX (SEP) and Brownsville, TX (BRO). This strong horizontal temperature gradient defines the location of the surface front. Also, notice the maximum temperature gradient continues above the surface front and levels off just above the jet core over Victoria, TX (VCT) at 250 mb.

The thermal wind (V_T) relationship can be applied to potential temperature gradients to determine the location of the geostrophic jet maxima (Palmen and Newton, 1969). In general, the strongest winds occur at the location where the vertically integrated temperature gradient is the largest. The thermal wind relationship is illustrated in Fig. 19. Notice in this figure that over Victoria, TX the potential temperature surfaces clearly slope to the south towards warm air with the strongest vertically integrated (or average)

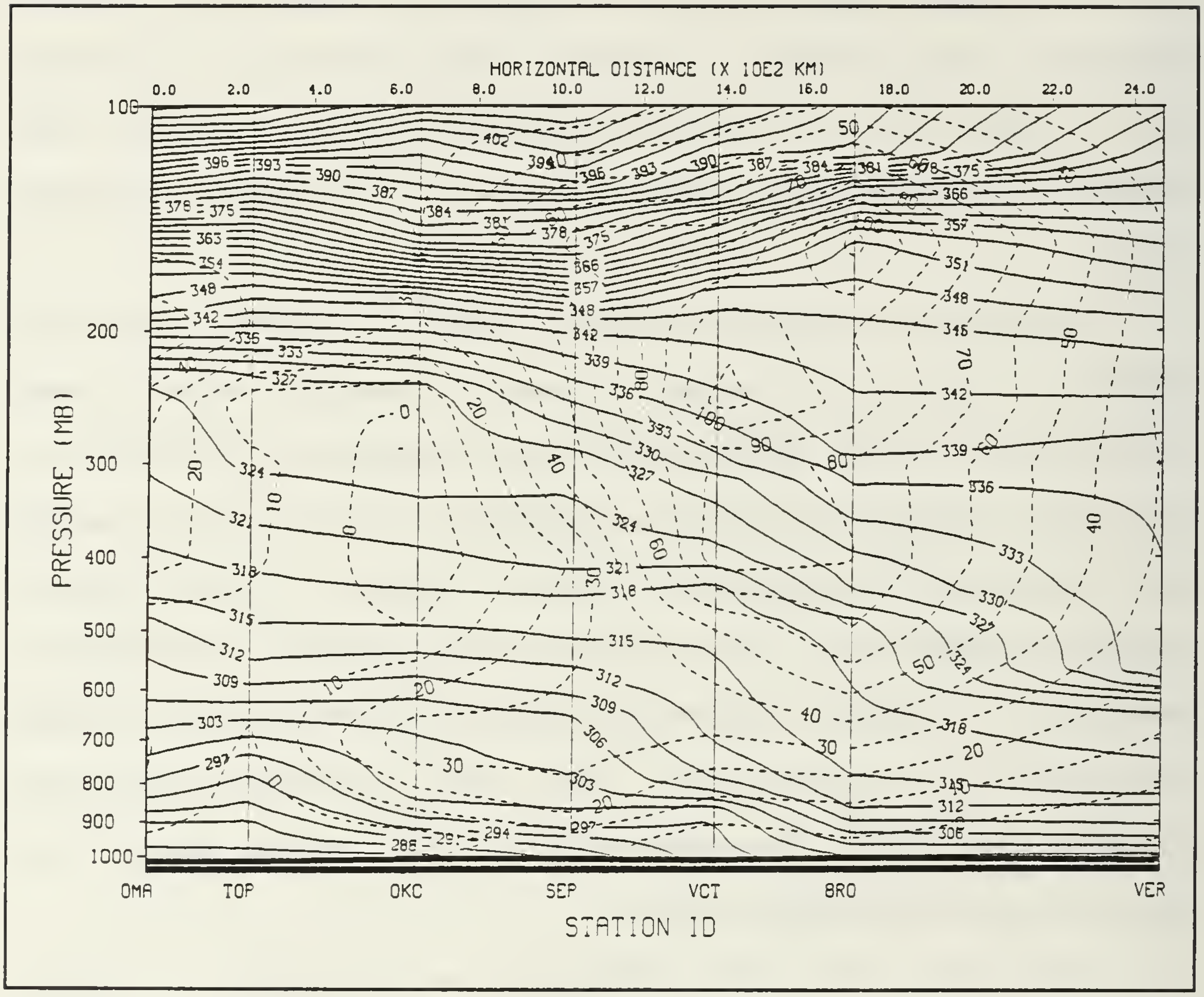

Fig. 19. Cross-sectional analysis of potential temperature between Omaha, NE and Veracruz, Mexico at 0000 UTC, 8 April 1984.

temperature gradient beneath the jet core. Also, the gradient of potential temperature reverses at 200 mb (above the jet core), which is the necessary conditions to cause the decrease in wind speeds with height at this level.

The tropopause is also defined in terms of potential temperature. The vertical location of the tropopause is marked by a rapid increase of potential temperature that indicates the atmosphere is stably stratified with height (Fleagle and Businger, 1980). Because of this stability, the tropopause acts as a lid or cap to vertical motion and usually marks the upper boundary of convective clouds. Only severe convection can penetrate through this stable layer and enter the lower stratosphere. Meteorologists use this relationship, combined with radar cloud top echo data, to decide if summertime convective activity has reached severe thunderstorm intensity.

The above potential temperature relationships are used to discuss the following three-dimensional display of clouds and potential temperature surfaces. Fig. 20 is a three-dimensional view of the entire IR subimage showing clouds and potential temperature surfaces. This figure was created with the same 8 X 8 pixel smoothing used to create Fig. 18. The viewpoint is from the west, so the squall line is the main group of clouds on the right, southern side of Fig. 18. Along with the clouds, there are four surfaces indicating the heights of the 300 K, 320 K, 340 K and 360 K potential temperature surfaces. The fifth surface is completely flat and has a height of zero to represent sea level. Potential temperature increases with height, so the 300 K surface is the first one above sea level and the 360 K is the last above sea level.

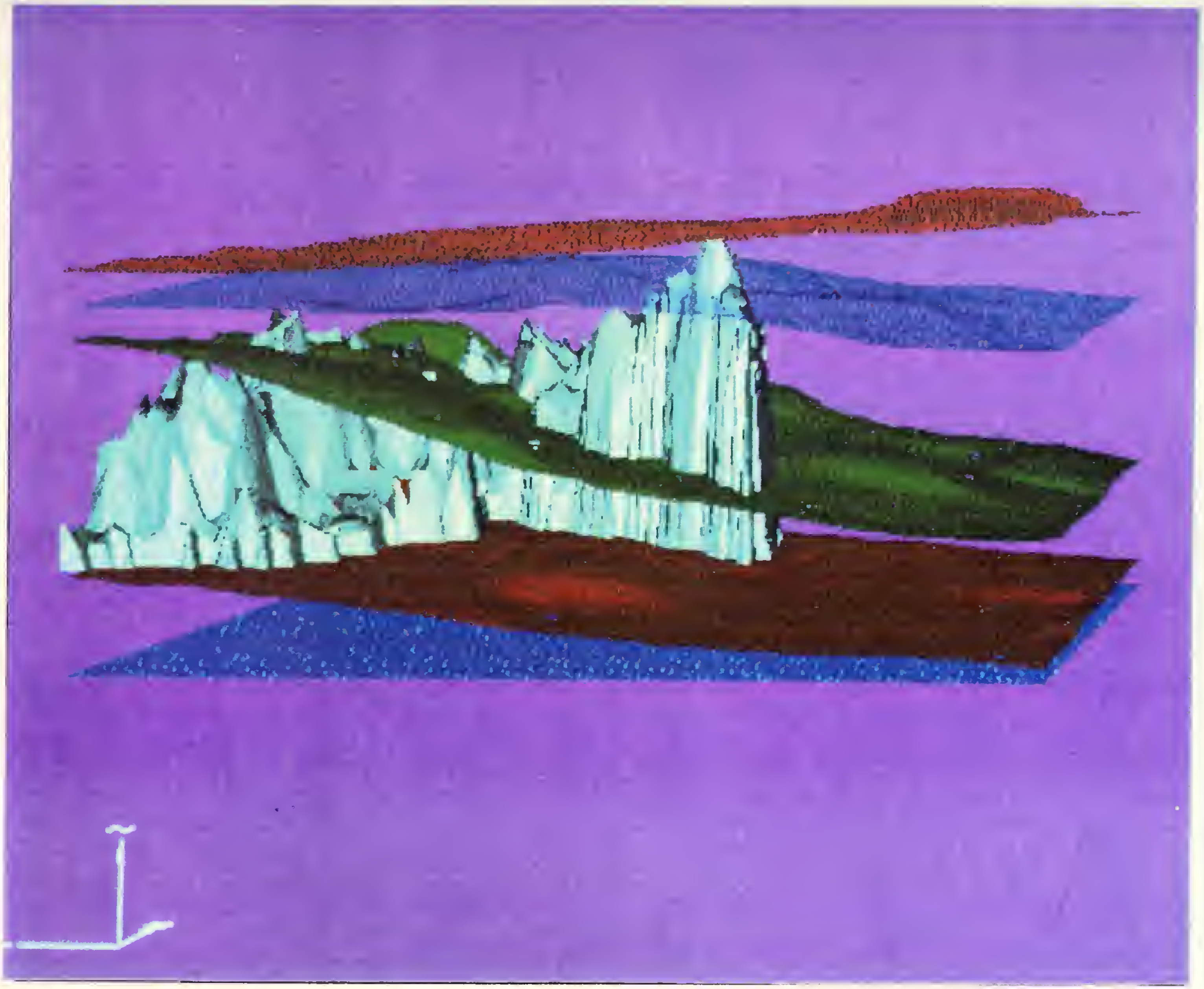

Fig. 20. Three-dimensional view of entire IR subimage from the west with four potential temperature surfaces: 300 K (red), 320 K (green), 340 K (blue) and 360 K (red).

Fig. 20 illustrates the possibilities of using three-dimensional images to interpret the structure of the atmosphere. The average slope of all four potential temperature surfaces is about 22.5/1000, or ten times the slope of the pressure surfaces in Fig. 18. Horizontal temperature gradients stand out at locations where the potential temperature surfaces tilt from north-to-south. The 320 K surface nicely illustrates this slope. It drops from over 10 km in the north to below 4.5 km in the south of this figure.

There is a nearly constant slope of the 300 K and 320 K potential temperature surfaces from the north to the south of this figure. Then these two surfaces begin to level off near the southern end of the squall line, which implies a nearly constant vertically averaged temperature gradient throughout the region of the squall line. Strictly from thermal wind considerations, the strongest winds should be located at the southern boundary of this constant temperature gradient. This location is determined because the thermal wind equation accounts for the variation of the coriolis force (f) from the pole to the equator where $V_T \propto 1/f$. So for a constant temperature gradient, the winds will be strongest further south where f is smaller. This implied location of the strongest winds can be verified in Fig. 21, which shows a hand analysis of wind speeds at 200 mb for 1200 UTC, 9 April 1984. As expected, the jet maxima crosses the southern edge of the squall line around 26° N.

The location of the tropopause can also be estimated by analyzing Fig. 20. A stably stratified atmosphere is indicated by a rapid increase of potential temperature with height. The close spacing of the potential temperature surfaces in the north of this figure (left side) indicates that here

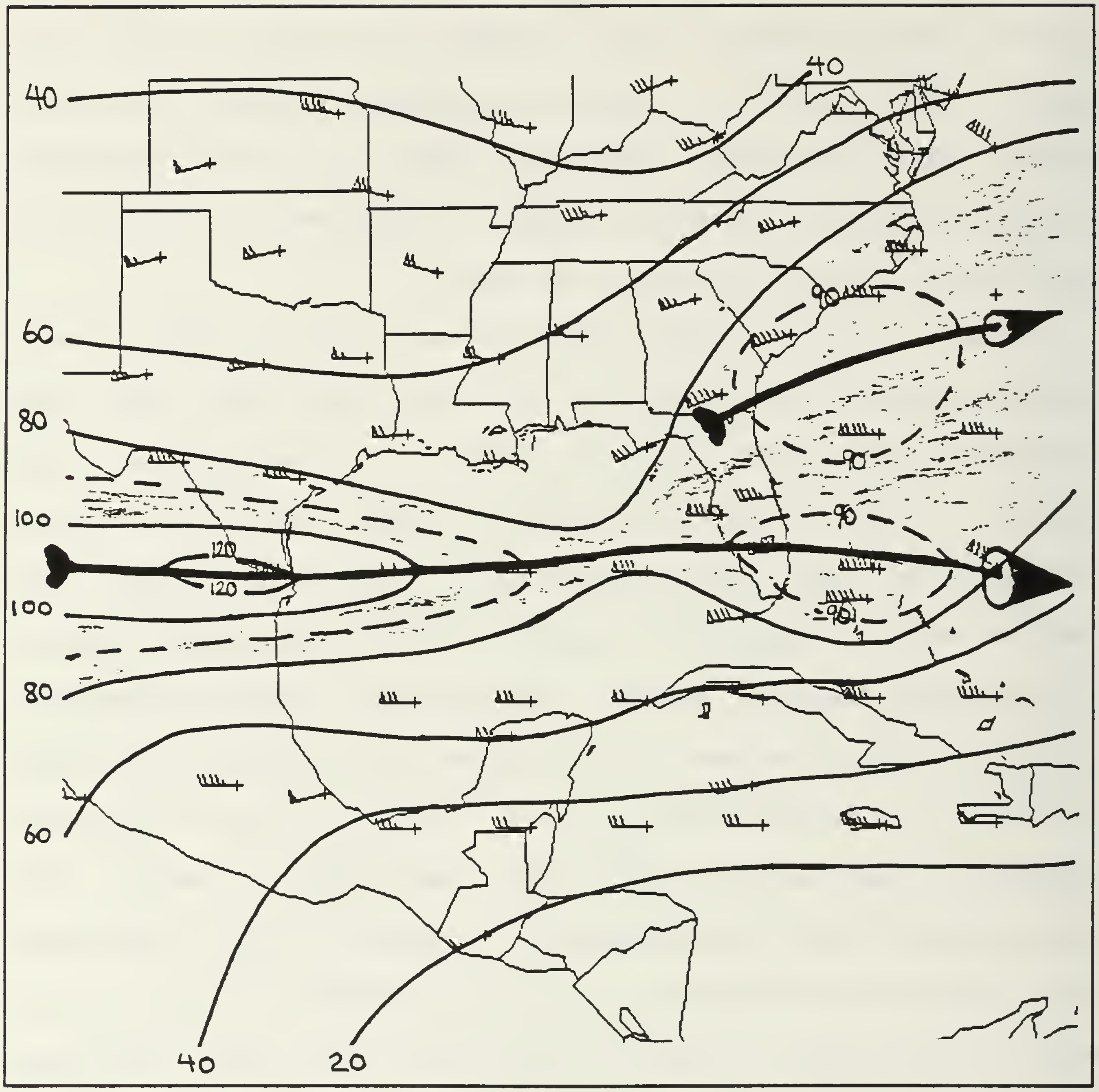

Fig. 21. Hand analysis of wind speeds at 200 mb for 1200 UTC, 9 April 1984.

the tropopause occurs near the height of the 320 K surface. The 320 K surface also corresponds to a "cap" in the convective activity in the left, northern side of this figure. The cap in convection at this location supports the placement of tropopause near the height of the 320 K surface in the north of this figure.

Over the squall line, the 340 K potential temperature surface appears to be a better indicator of the tropopause than the 320 K surface. The 340 K surface remains relatively flat until reaching the edge of the squall line. Then it begins to slope down towards the warm air south of this region. The 360 K surface lies above, and almost parallel to the 340 K surface until reaching the southern tip of the squall line. This close packing of potential temperature surfaces indicates the stability associated with the tropopause. Over Tampa Bay, FL the tropopause height was determined to be 11,300 m from sounding data. This height is only 500 m less than the 11,800 m height of the 340 K surface that passes over Tampa Bay, FL (Fig. 22)

The 340 K surface varies from 12,000 m, where the squall line passes over Florida, to around 10,800 m, at the southern tip of the squall line. Svetz (1985) determined the average tops of clouds in this region to range from 11,900 m to 11,000 m. His analysis incorporated the enhanced IR image and Tampa Bay, FL sounding data to estimate cloud heights. His estimate of cloud heights matches the range of the 340 K potential temperature surface quite well. The previous figures demonstrate the potential of having all the information in two displays. In this example, the majority of cloud top heights could have been determined using only the three-dimensional analysis (Fig. 20) and data from Fig. 22. If a height bar is added to the three-dimensional

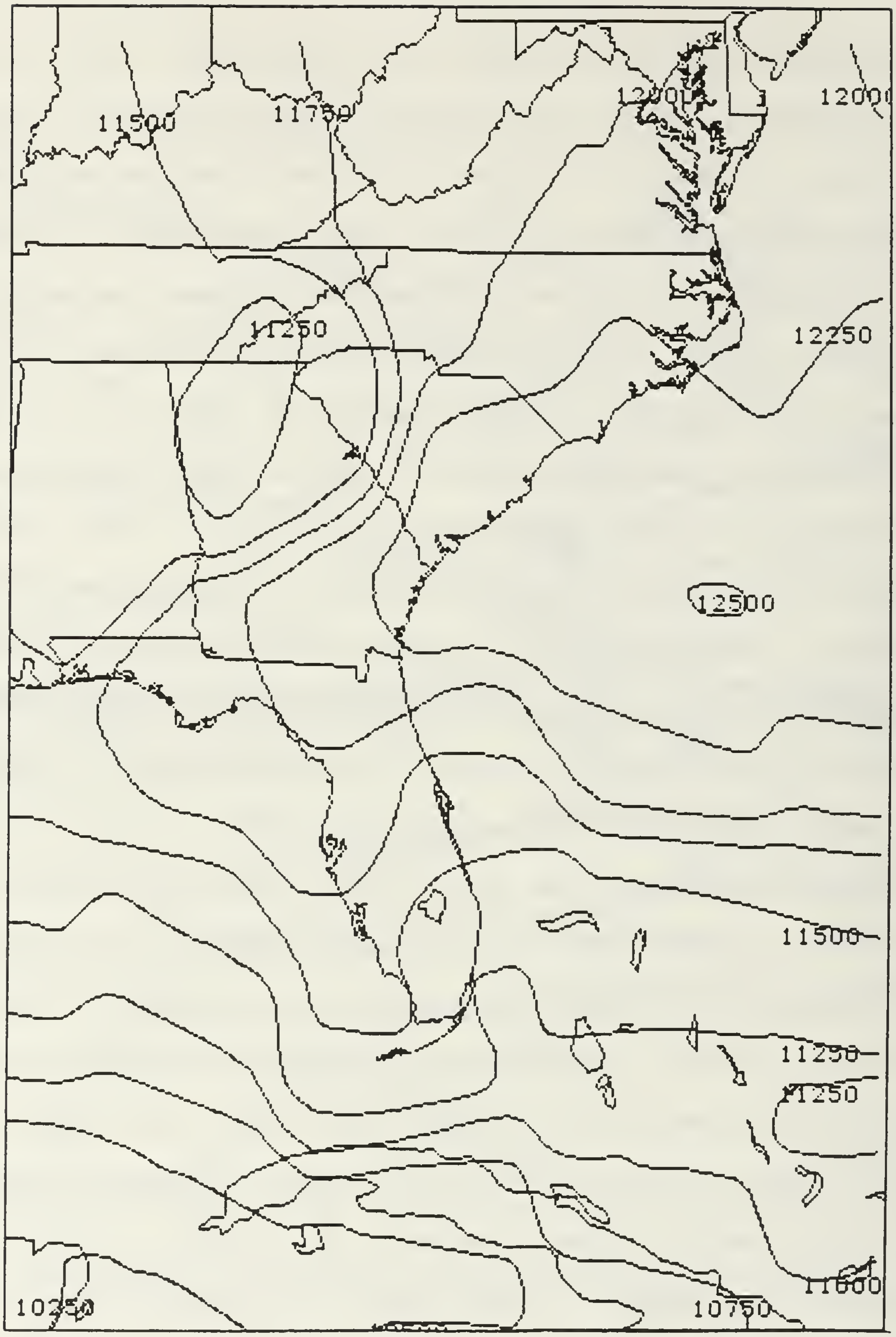

Fig. 22. GEMPAK contoured analysis of the 340 K potential temperature surface over the entire satellite image area (height in meters).

display, cloud tops and tropopause heights can be inferred by examining one display of information.

C. CLOUDS AND LCL BASES

One of the objectives of this thesis was to use LCL's as a "first guess" to cloud base heights in the three-dimensional cloud model. The LCL represents the height to which an air parcel must be lifted, and thereby cooled, before saturation occurs. Once an air parcel reaches its LCL, a cloud should form with its base at the LCL. As mentioned in Section 3.B.1, LCL's were determined with the same algorithm that was used to calculate cloud top heights. GEMPAK software was used to compute an objective analysis of LCL temperatures throughout the entire satellite image. Then, the heights of these LCL temperatures were determined from the 1200 UTC, 9 April 1984 sounding data for Tampa Bay, FL.

After analyzing the cloud bases determined from the LCL data, it became apparent there was an error in the technique used to compute LCL heights. In general, cloud bases were computed to be higher than the heights expected with this algorithm. This error is illustrated in Fig. 23, which shows the 1200 UTC, 9 April 1984 sounding profile for Tampa Bay, FL. The LCL occurs at the height where the surface mixing ratio and surface dry adiabat lines intersect on the sounding. This intersection occurs at 980 mb on the Tampa Bay sounding (position A). The 980 mb level intersects the temperature profile at a value of 19.5° C (position B). Initially, the author assumed this was the technique that GEMPAK used to determine LCL temperatures; however, the technique that GEMPAK uses is slightly different.

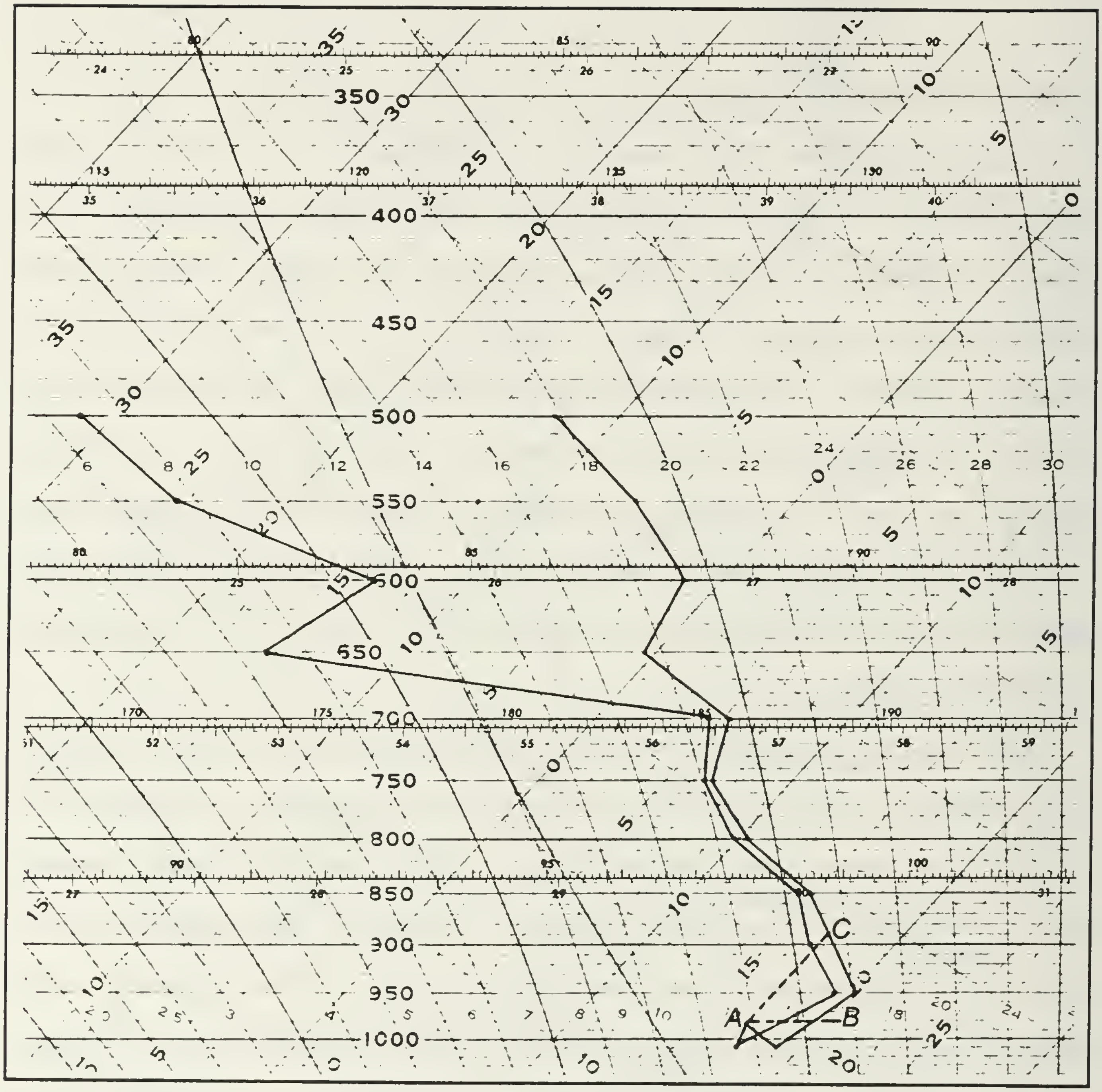

Fig. 23. The Tampa Bay, FL sounding for 1200 UTC, 9 April 1984, illustrating the error in the algorithm that was used to calculate LCL heights.

GEMPAK returns a temperature for the LCL that corresponds to the temperature line that intersects the mixing ratio and dry adiabat lines. In Fig. 23, the intersection of these three lines occurs at 17° C, which is also at position A. For a temperature of 17° C, the algorithm used to compute LCL heights calculates a height that occurs near 890 mb on this sounding (position C). The difference between positions B and C is 90 mb, which causes a 740 m height error for the LCL in this example. The general trend was an error between 500 m to 1,000 m for the LCL heights computed from the objective analysis of LCL temperature data. As a result of this error, in many of the stratus cloud regions, the LCL was higher than the cloud tops and could not be used. This inconsistency in heights was corrected by setting the cloud base to a user preselected default base height in these regions.

The initial results of using LCL's for cloud base heights are still encouraging. Over most of the cloud regions analyzed, the LCL appears to be a good indicator of a realistic cloud base height. Fig. 24 illustrates the effectiveness of using LCL's as the cloud base height in three-dimensional cloud models. In this figure, the view is from the west, so the squall line is the main mass of clouds in the center of Fig. 24. The clouds on the left, north side of this figure are low stratus clouds over the southern Gulf States. Note that the majority of cloud bases have a tapered look that gives them a realistic appearance.

Because of the LCL determination error, only 57.37% of the cloud pixels in this figure were found to have consistent cloud base heights that did not exceed their cloud top heights. The large regions of stratiform clouds throughout Fig. 24 are the main reason for the high number ofinconsistent

Fig. 24. Results of using LCL's for cloud base heights. The view is from the west with the squall line, the main mass of clouds, in the center of this figure.

cloud bases in this example. In the regions of inconsistent cloud base heights, the bases were set to a default height of 915 m.

A new algorithm must be developed before any accurate LCL bases can be determined from the available sounding data. The algorithm could still use the objective analysis capabilities of GEMPAK to aid in this process. One possible solution involves computing cloud base heights from sounding information and an objective analysis of LCL heights in units of millibars. This method would be similar to the current method in that LCL heights could be computed by locating the height on the sounding where a given pressure level occurs. It is also possible that there may be a combination of GEMPAK subroutines that could directly provide an objective analysis of the heights of all LCL's over a user selected area.

Eventually, techniques for determining accurate cloud base and cloud top heights may provide the data needed to correctly model three-dimensional clouds with the "one layer" approach used in this thesis. The term "one layer" is emphasized because the atmosphere is more complicated and usually contains multiple layers of clouds. However, there is no automated method of determining the data required to model multi-layered clouds in three-dimensions. Because the atmosphere contains multiple layers of clouds, the cloud display technique used in this thesis represents an approximation to the vertical structure of clouds in the atmosphere.

V. CONCLUSION AND RECOMMENDATIONS

A. CONCLUSION

An improved technique for displaying clouds and synoptic weather data in three-dimensions has been presented in this thesis. The process of going from IR brightness temperatures to a three-dimensional model of clouds is based on the assumption that clouds are perfect black bodies and in local equilibrium with their surrounding environment. These assumptions appear to hold for the majority of cloud pixels in the squall line example analyzed here. The only clouds that could not be accurately modelled were the thin cirrus clouds surrounding the squall line.

The data set used in this thesis consist of GOES IR and visible satellite imagery and space shuttle photography of a well developed squall line over the Gulf of Mexico on 9 April 1984. This squall line was chosen because of its distinct vertical cloud patterns, which includes a well defined back edge and several convective turrets embedded in the squall line's central cloud mass.

The memory restrictions on the VAX/VMS computers used for this thesis precluded a complete analysis of the entire IR/visible subimage in full resolution. However, a comparison of an enlarged visible image was made with a graphically generated overhead view of the same subscene in half resolution. This comparison demonstrates the high degree of visual realism obtainable with the three-dimensional display technique. Visual realism is a primary goal of the development of three-dimensional imagery. This realism, obtained in the higher resolution displays, is also necessary for analyzing

small scale features that are embedded within cloud systems such as the convective turrets shown in Fig. 15b. Ultimately, any three-dimensional display technique should have the capability to create full resolution displays from the most detailed data sources available if these displays are to have general applications for mesoscale forecasting.

The squall line's vertical structure was analyzed by using the rotation capability of the MOVIE.BYU display software to view this cloud system from an oblique orientation (Fig. 15b). Locations and relative heights of individual clouds could be seen easily with this technique of viewing clouds. The oblique viewing process also highlighted the position and vertical extent of two convective turrets that were embedded in the squall line. The larger of the two convective turrets was also easy to locate in the space shuttle photograph (Fig. 16). However, the smaller turret did not clearly stand-out in this same image. The smaller turret was probably "real" as suggested by the colder IR temperatures (Fig. 15a) and notched cloud patterns seen in the higher resolution three-dimensional display, satellite image and space shuttle photograph. The extreme convection associated with this squall line and a three minute separation between the satellite and shuttle imagery are two factors that may explain why the smaller turret could not easily be located in the space shuttle photograph (Fig. 16).

The addition of shadows from a simulated light source is a useful capability of the graphics software demonstrated in this thesis. The shadowing capability made it possible to see the stepwise intrusions the larger convective turret made as it entered the tropopause (Fig. 15b). A possible benefit of using a simulated light source in three-dimensional cloud displays is that high

resolution three-dimensional cloud scenes could be analyzed for convective turrets; thus, three-dimensional imagery could be a possible aid to severe weather forecasters.

A three-dimensional image of clouds and height levels in the atmosphere provides pilots a useful source of visual information for determining the locations of clouds along their route as seen in Fig. 17. A major concern of pilots is whether they will encounter clouds, reduced visibility, or severe weather along a given flight path. By using a three-dimensional presentation of clouds, forecasters could convincingly brief pilots on the vertical extent of clouds and severe weather in relation to the pilots' flight path. This capability also could be used to simulate a "fly-through" of the weather by constructing three-dimensional loops of the current satellite image that apply to standard aircraft routes. Such a presentation would enable pilots to familiarize themselves with the weather along their route before they even began their flight.

Three-dimensional views of clouds and pressure surfaces enable forecasters to compare the vertical structure of cloud systems to commonly used indicators of the geostrophic wind and cyclone development. A reduced resolution view of clouds and pressure surfaces is presented in Fig. 18. The pressure surfaces in this example display a slight increase in thickness from the north to the south of Fig. 18. This increase in thickness indicates the atmosphere is on the average warmer in the south of this figure. The pressure surfaces vary less than three hundred meters in the vertical over the 1,300 km horizontal area of Fig. 18. Therefore, even with an 8-to-1 vertical-to-horizontal scaling factor, it is impossible to see any significant pressure

variations with this display technique. The direction of the geostrophic wind and location of low and high pressure centers cannot be determined with this method of displaying clouds and pressure surfaces. Another technique should be developed that would bring out the details of pressure variations in the atmosphere when displayed in three-dimensions.

Displays of clouds and potential temperature surfaces can be used to infer the dynamical structure of the atmosphere. One example of combining three-dimensional clouds and potential temperature surfaces is given in this thesis (Fig. 20) to demonstrate some well known atmospheric dynamic relationships. The height of the tropopause is estimated by looking for regions where the potential temperature surfaces flatten out and become closely spaced in the vertical. These locations are associated with a cap in the less severe convective activity throughout much of this squall line example. The slope of potential temperature surfaces can be used to estimate the strength and probable locations where strong wind speeds occur. At 1200 UTC, 9 April 1984 there was a very pronounced temperature gradient over the squall line cloud system as seen in the three-dimensional display (Fig. 20). As expected from thermal wind considerations, this temperature gradient led to the formation of a sub tropical jet that crossed the southern tip of the squall line (Fig. 21).

This thesis also attempted to solve the problem of how to determine cloud base heights from routinely available weather data and incorporate these bases into three-dimensional cloud models. While the necessary software was successfully developed and tested, the author's initial misinterpretation of the GEMPAK LCL temperature values resulted in an incorrect algorithm for determining LCL heights. The cloud bases determined from LCL data and

displayed in this thesis are from 500 m to 1,000 m too high (Fig. 24). However, there is still a high degree of realism to this method of displaying cloud base heights. This realism suggests that a corrected algorithm for determining LCL heights could give meaningful values of cloud base heights for use in three-dimensional cloud models.

The technique of displaying clouds with pressure, potential temperature and LCL base heights illustrates how large quantities of information from separate data sources can be combined in one three-dimensional display. Being able to combine large volumes of data and quickly display this information from several perspectives is the main reason for creating three-dimensional displays of the atmosphere. It is the authors personal hope that some form of a three-dimensional display technique eventually will be used to create useful views of the atmosphere for instructional purposes. Also with some improvements, meteorologists should be able to use three-dimensional displays of the atmosphere to help them efficiently determine the current causes of weather. Hopefully, by providing a better understanding of the structure of the atmosphere and causes of weather, three-dimensional displays also will lead to improved forecasts of the future weather.

B. RECOMMENDATIONS FOR FUTURE RESEARCH

The following are some recommendations for future research that should improve the accuracy and applicability of the three-dimensional software used in this thesis:

1. Improved height determination

A major limitation exists in the current technique of determining the heights of clouds and LCL's. The reason for this limitation is that only one atmospheric sounding is used to determine the heights of all the cloud tops and LCL's throughout the entire subscene. Fig. 25 illustrates the discrepancy in heights that occurs when using only one sounding to represent the atmospheric structure of an entire cloud scene. Assume that two cloud pixels have the same temperature, but one cloud pixel is in the north, CPn, and the other is in the south, CPs. The correct method of determining the cloud top heights is to use the northern sounding for CPn and the southern sounding for CPs. Using this method, CPn will have a lower height than CPs as shown in Fig. 25, with $hn < hs$. However, when just one sounding is used for both cloud pixels, CPn and CPs both are determined to have the same height.

When only a southern, warmer sounding is used to determine cloud heights, all the northern cloud tops are placed at higher levels than their true height. Fig. 26 shows the results of using a northern and southern sounding for determining the heights of all the clouds in the original IR/visible subimage. Both of these three-dimensional images show the clouds and a semi-transparent 300 mb reference surface with a viewpoint from the south. Cloud heights were determined from the Tampa Bay, FL sounding in Fig. 26a and the Dulles International Airport (IAP), MD sounding in Fig. 26b. Notice how several groups of clouds protrude above the 300 mb surface in the northern, back side of Fig. 26a. These same clouds are below the 300 mb surface in Fig. 26b; and the squall line in the southern, front side of this figure is lower than in Fig. 26a.

Fig. 25. Illustration of the correct procedure to determine cloud pixel heights for two pixels at different locations. The pixel located in the northern, colder atmosphere (CPn) has a lower height than the pixel located in the southern, warmer atmosphere (CPs). However, in this example both pixels have the same IR brightness temperature.

(a)

(b)

Fig. 26. Two versions of the satellite image in three-dimensions. Clouds determined from the Tampa Bay, FL sounding (a), and clouds determined from the Dulles IAP, MD sounding (b).

Realistically, the cloud structure should be a combination of Figs. 26a and 26b; with the squall line placed higher, as in Fig. 26a, and the northern clouds being lower, as in Fig. 26b. The amount of error in cloud top heights for this example was between 1030 m to 1730 m for a temperature range of 270 K to 215 K. These height errors represent differences in height for the same IR brightness temperature determined from the Tampa Bay and Dulles IAP sounding data for 1200 UTC, 9 April 1984. Also note, this discrepancy applies to the heights of LCL's, because the same method was used to determine the height of each LCL from its temperature.

Since the atmosphere frequently has strong gradients of temperature in the east-west direction, the problem of determining cloud top and LCL heights is not limited to north-south variations of the atmospheric structure . Also, very large height errors (over 6 km) can occur when atmospheric inversions result in a warm IR brightness temperature being given a higher than true height. These situations cannot be resolved when only using one sounding to represent the cloud structure of the atmosphere. Therefore, this height determination problem is a general problem that occurs throughout any satellite image to be modelled in three-dimensions. A method of using all available sounding data to determine cloud and LCL heights must be developed before precise applications of this three-dimensional display technique are possible.

2. Improved cirrus representation

As previously mentioned, the current algorithm that calculates cloud top heights does not accurately determine the correct height for thin cirrus clouds. This occurs because thin cirrus is not a perfect black body. The cirrus

allows radiation from below to pass through to the IR sensor above. This causes the IR sensor to measure brightness temperatures that are too warm for thin cirrus clouds. As a result of these warmer than true temperatures, thin cirrus clouds are placed too low with the algorithm used in this thesis.

Thin cirrus clouds are also difficult to model in three-dimensions because they are layered clouds in the upper troposphere. Therefore, extending thin cirrus clouds as one solid cloud model to a low level base height is unrealistic. A technique for determining more accurate cirrus heights and estimating cirrus thickness should be developed. These cirrus clouds could be displayed as a separate layer of clouds in the three-dimensional model. A possible solution would be to use reflectivity data along with IR data to estimate height and thickness of cirrus clouds. The algorithm could assume that cloud pixels with an albedo below a cutoff reflectivity value and brightness temperature are thin cirrus. The height and base of these clouds could then be adjusted based on their albedo value. Some success in automatically determining cloud types from IR and visible reflectivity data has already been demonstrated (Wash, *et al.*, 1985).

3. Increased resolution

An increase in the combined resolution of cloud and atmospheric surface models is another improvement that would advance the usefulness of this display software. The current method of creating combined cloud and atmospheric surfaces must be changed. The problem results from the displays of combined data sources, such as Figs. 18 and 20, where the atmospheric surfaces require roughly four times the number of polygons than are used to model the clouds. A routine similar to CLDGEN should be designed to model the

atmospheric surface variations separately from clouds. Possibly a technique could be designed to use a variable resolution for modelling atmospheric surfaces. More polygons could be used (as required) to model surface changes in regions of large variations.

4. Improved pressure display technique

An improved technique to display the vertical variations of atmospheric pressure should be developed. One technique that could be used to depict the variations of pressure with height is a three-dimensional display of D-values. D-values are deviations of the height of pressure values from the standard atmospheric height of that pressure value. For example, two-dimensional displays of D-values for hurricanes show a distinct "bulls eye" pattern of large negative D-values centered over the hurricanes eye, or low pressure center (Byers, 1974). A display of D-values in three-dimensions would be useful for locating areas of high versus low pressure in the atmosphere. The high and low pressure centers could be highlighted by using separate colors for positive and negative D-values. To illustrate the three-dimensional structure of pressure changes within the atmosphere, D-value displays would be an improvement over the current pressure display technique.

5. Other data sources

A general purpose method of producing three-dimensional images of other atmospheric variables should be developed. Possible variables that could be used for forecasting purposes when displayed in three-dimensions are:

a. wind speed and direction,

b. vorticity values and vorticity advection,

c. temperature and thermal advection and

d. moisture.

This technique would probably involve using a four-dimensional array of data for each type three-dimensional variable to be analyzed. Values for the variable of interest would need to be stored at each X, Y, Z point. Then by picking out a cutoff value, sections along each vertical segment could be analyzed to see where the cutoff value is first encountered and where the variable falls below that cutoff value again. These segments then could be constructed into three-dimensional models of the atmospheric variable. A problem would exist for those situations where the variable of interest crosses back-and-forth over the desired cutoff value more than once in the vertical. This and other problems, such as thresholding cutoff values and using transparency and color effectively, would need to be solved for this technique to work successfully.

There are certainly other improvements that could be made to the software used to create the three-dimensional displays in this thesis. Several good suggestions were made by Meade (1985) and Crosby (1986). The use of a height bar and geopolitical boundaries for spatial orientation are two of their recommendations that would give this display more realism. Also, using an array processor, as suggested by Crosby (1986), would currently be required before this software could be used to create "real-time" three-dimensional displays of the atmosphere for operational forecasters. In the future, it may be possible to use a combination of data sources; such as IR derived cloud heights, Doppler radar measured wind speeds, satellite soundings and mesoscale numerical weather predictions, to forecast the short term development of cloud systems. Given accurate forecasts, an advanced version

of this three-dimensional display software could possibly present the movement and development of these "predicted clouds" before they even occur.

APPENDIX A.1

CODE CHANGES TO CSU SOFTWARE

This appendix explains the code changes that were made to the CSU version of the software that creates three-dimensional cloud scenes.

The following changes were made to the routine DEFSCT:

a. DEFSCT (INTCLD and CLDGEN too) have been parameterized. By doing this, future versions of this code should not have to be "rewritten" to handle larger subimages in full resolution. The parameter used in these three programs is called MAXRES. To increase the processing resolution of this software, simply change MAXRES to the new maximum resolution in each program, recompile these routines and relink the main programs. However, the size of your main executable (.EXE) is restricted by the system's memory configuration that you run this software on. Also, larger resolutions affect the total number of polygons that are used for large cloud scenes, which in-turn affects the size of the MOVIE.BYU DISPLAY program that is needed to display these cloud scenes. At present, the DISPLAY program can only handle 25,000 polygons at a time, and this is less than the number required for the large cloud scenes in 256 X 256 resolution. For this reason, all the cloud scenes in this thesis had a resolution of either 64 X 64 or 128 X 128.

b. The display code within DEFSCT was rewritten using standard Display Management Subsystem (DMS) function calls. This now makes DEFSCT "device independent" as long as a DMS interface has been written for the device you plan to run DEFSCT on.

The following changes were made to the program INTCLD:

a. As mentioned above, INTCLD has been parameterized and the display code within INTCLD has been rewritten using standard DMS function calls.

b. The I/O of satellite data within INTCLD was also rewritten. The new version uses direct access I/O to read in the data associated with the subimage. This speeds up this process and makes that section of code easier to understand too.

c. The thresholding process in INTCLD was changed to be interactive. This allows the user to rethreshold a subimage without having to rerun INTCLD (as was the case in the previous version).

d. A routine has been added to INTCLD to facilitate future versions of this code that use other data sources such as AVHRR IR imagery. This routine, called CHOICE, has the user specify a satellite data type. The current code only has one "choice" of data, which is GOES. CHOICE simply sets a variable called SAT_TYPE to the name of the satellite data type chosen. SAT_TYPE is then passed back to main routine INTCLD for use as a processing flag.

e. A complete new section of code was added to INTCLD to handle the processing of LCL data. This process is accomplished within the routine CAL_BOT_HGT. Now there are two methods of handling the cloud base: 1) the old method of using a flat base, and 2) the new technique of computing base heights throughout the subimage using heights computed from an objective analysis array of LCL temperatures. The user must first create the objective analysis of the LCL values over the region defined by the satellite image before the LCL heights can be accessed by INTCLD. Also, INTCLD expects these heights to be stored in a file named OA_LCL.DATA under the directory that INTCLD is run from.

f. In conjunction with e. above, another section of code was added to INTCLD to create a diagnostic array that contains "flags" showing the location where the computation of the base height exceeded the top height (i.e. **LCL HEIGHT - TOP HEIGHT > 0**). The magnitude of the difference is stored using a number scheme to highlight differences in increasing amounts (i.e. 500 m, 1000 m, etc.). The graphical results of this process are then output to the disk file CLOUD_PICTURE.DATA. These results can be displayed to a graphics device by running the program MAKE_CLD_ PICTURE. This process was mainly added to help track down the problem of inconsistent base heights but may come in handy in the future testing of a new base height determination algorithm.

g. Also in the way of diagnostic code, a diagnostic print flag was added to some of the routines in INTCLD. When this option is requested, at the beginning of execution of INTCLD, diagnostic messages are written to the screen . Also, a diagnostic print file is created and put on the system (at the user's request) when this diagnostic feature is used. This feature should be expanded in future versions of INTCLD to help the user keep track of all the processing that occurs in this rather complex program.

h. Many other changes were made to INTCLD to make it easier to understand and hopefully work with in the future. Also, documentation was added to all of the new code and most of the old code that was rewritten.

The following code changes were made to the program CLDGEN:

a. As mentioned above, CLDGEN has been parameterized to handle future versions of these routines that allow larger resolution.

b. CLDGEN was also restructured to work "without" the topography data for a given subimage. This was done to avoid having to use topography data over the region of the southeastern U.S. used in this case study. Additionally, the new version of this code is not structured to handle topography data. If this

topography feature should be desired, in future versions of the three-dimensional modelling process, some new programs (similar to the old DMA512) must be written to handle topography data from varying sizes of satellite images. Recall, the CSU version of this software was only structured to handle 4.27° X 4.27° areas of the Northwestern hemisphere.

c. Another change to CLDGEN involved incorporating new format statements updated in the 1987 edition of MOVIE.BYU. These changes were made to the routine GEOWRT, which writes the geometry file to disk storage.

d. Also, some of the routines in CLDGEN were restructured to make them easier to read and hopefully understand as well.

APPENDIX A.2

USE OF DEFSCT

The program DEFSCT is used to select the satellite subimage to be modelled in three-dimensions. To run DEFSCT you must be in the TAE command mode. Also, there should be a TAE Program Definition File (PDF) for DEFSCT within your file for the following instructions to work properly.

Enter DEFSCT at the TAE prompt. *(Note: currently DEFSCT only works properly on system DONALD, the IP8500 graphics device.)*

>DEFSCT <CR>

ENTER DESIRED IMAGE PROCESSING RESOLUTION, CHOICES ARE:

(1) - 64 X 64	== 0 PIXEL SMOOTHING FOR A 64 X 64 SUBIMAGE
	== 2 PIXEL SMOOTHING FOR A 128 X 128 SUBIMAGE
	== 4 PIXEL SMOOTHING FOR A 256 X 256 SUBIMAGE
	== 8 PIXEL SMOOTHING FOR A 512 X 512 SUBIMAGE
(2) - 128 X 128	== 0 PIXEL SMOOTHING FOR A 64 X 64 SUBIMAGE
	== 0 PIXEL SMOOTHING FOR A 128 X 128 SUBIMAGE
	== 2 PIXEL SMOOTHING FOR A 256 X 256 SUBIMAGE
	== 4 PIXEL SMOOTHING FOR A 512 X 512 SUBIMAGE
(3) - 256 X 256	== 0 PIXEL SMOOTHING FOR A 64 X 64 SUBIMAGE
	== 0 PIXEL SMOOTHING FOR A 128 X 128 SUBIMAGE
	== 0 PIXEL SMOOTHING FOR A 256 X 256 SUBIMAGE
	== 2 PIXEL SMOOTHING FOR A 512 X 512 SUBIMAGE

>2 <CR> *(Note: currently the maximum resolution that works for large cloud displays is 128 X 128. This has to do with the total number of polygons or finite elements (FEs) that can be displayed by the current version of MOVIE.BYU.)*

ENTER SCALED TOPOGRAPHIC IMAGE (I-STI) FILE NAME

> <CR> *(Note: Topography Models were not used in this thesis. The CSU topography programs must be modified before this option could be used.)*

DO YOU WANT TO DISPLAY THE SCALED TOPOGRAPHIC IMAGE?

>NO <CR>

ENTER INFRARED CLOUD IMAGE (I-IMG) FILE NAME

>SQLIR1 <CR> *(This is the file name of the GOES infrared image you are going to work with. Use only the file name, the file extension must be .IMG.)*

DO YOU WANT TO DISPLAY THE INFRARED CLOUD IMAGE?

>YES <CR> *(At this point the infrared image will be display to the IP8500 graphics device.)*

ENTER THE VISUAL CLOUD IMAGE (I-IMG) FILE NAME

> <CR> *(Note: Only IR images were used for the squall line case study. There may be some minor code modifications that are necessary before visible imagery can be used for the thresholding process.)*

ENTER 3-D CLOUD-TOPOGRAPHY MODEL (O-CTM) FILE NAME

>TEST1 <CR> *(This file name will be used as the qualifier for outputing program results to.)*

DO YOU WANT TO DEFINE THE AREA FROM THE TOPOGRAPHY IMAGE?

>NO <CR>

POSITON THE CURSOR ON THE U.L.C. OF YOUR SUB-IMAGE
WHEN YOU ARE READY, HIT THE JOYSTICK ENTER BUTTON.

(Now use the joystick to position your cursor on the upper left hand corner of the subimage your interested in. This is an interactive process, so don't worry about making a mistake. Also , you can use a <CR> instead of the ENTER BUTTON.)

> <CR>

THE X AND Y COORDINATES ARE 38 AND 276
ARE THESE SATISFACTORY?

>Y <CR>

VALID SIDE LENGTHS ARE: 64 128 >64 <CR>	*(This side length determines the size of your subimage within the IR satellite image on the screen. This subimage will be modelled in three-dimension with the smoothing scheme governed by the processing resolution already selected.)*

DO YOU WANT TO DISPLAY A BOX AROUND YOUR DEFINED AREA?

>Y <CR> *(Now your subimage area will be highlighted within a boxed region on the screen. If you don't like the chosen area, repeat this process until you are satisfied.)*

IS THE DEFINED AREA SATISFACTORY?

>Y <CR>

DEFSCT DONE

DEFSCT creates the DEFSCT.DAT file which is used by routines INTCLD and CLDGEN for controlling the modelling process. The structure of this file for the previous example follows:

a	-- 38 276 64 1	(startX, startY, subimage size, & smoothing factor)
b	-- 3DMODEL.STI	(name of scaled topographic image file*)
c	-- TEST1.STM	(name for scaled topography model -- when used)
d	-- SQLIR1.IMG	(name of IR image file)
e	-- TEST1	(file qualifier for INTCLD and CLDGEN's use)
f	-- TEST1.SCM	(name for scaled cloud models)
g	-- TEST1.CTM	(name for cloud topography models -- when used)
h	-- NONE	(indicates no visible file is being used)

* To "get around" a restriction of the CSU version of this software, a file name of 3DMODEL.STI must be in the directory that DEFSCT is being run from. This stems from the previous use of scaled topographic image files for creating the combined cloud topography files. The code should be modified to take this requirement out).

APPENDIX A.3

USE OF INTCLD

The program INTCLD is used to processes the IR subimage to determine the height and base of each cloudy pixel within the subimage previously selected by running DEFSCT. The values for cloud pixel heights are then written to two files for use by CLDGEN. To run INTCLD you must be in the TAE command mode. Also, there should be a PDF for INTCLD within your file for the following instructions to work properly.

Enter INTCLD_DONALD or INTCLD_GOOFY at the TAE prompt. Use the appropriate PDF for the system you are on.

>INTCLD_DONALD <CR>

*** INTCLD *** WANT TO PRINT DIAGNOSTICS?

>N <CR>

(Diagnostics are used to get keep a record of the processing that occurs while INTCLD is running.)

ENTER SATELLITE DATA TYPE. CHOICES ARE:
(1) GOES

>1 <CR>

(The current choice is limited to GOES IR. Future version of this software should allow other data types such as AVHRR.)

ENTER IR CLOUD/NO CLOUD THRESHOLD (0-254)

>84 <CR>

(This is the threshold for which IR temperature values to retain in the modelling process. This thresholding process is interactive, so the value you pick now is not critical at this point.)

DO YOU WANT TO DISPLAY THE SUB-IMAGE(S) ON THE GRAPHICS DEVICE? Y/N

>Y <CR>

(In most cases you will probably want to display the subimage for thresholding purposes.)

VALID ENLARGEMENT FACTORS ARE: 1 2 4 8
ENTER AN ENLARGEMENT FACTOR

>2 <CR>

(A larger factor here simply causes your image to be displayed larger. This value does not affect other portions of INTCLD.)

DO YOU WANT TO VIEW THE SQLIR1 IMAGE? Y/N

>Y <CR>

DO YOU WANT TO ZERO THE BACKGROUND BRIGHTNESS? Y/N

>Y <CR>

(Chosing yes causes all IR pixels less than 84 to not be displayed.)

DO YOU WANT TO REDEFINE THE THRESHOLD? Y/N

>N <CR>

(At this point, you have the option to select another threshold if the value of 84 is not desired. Notice that selecting different thresholds changes the total number of connected cloud pixels that remain in your thresholded image. Since DISPLAY can only handle 30 models at a time, it's best to use a threshold that retains between 20 - 25 clouds.)

ENTER THE CLOUD BASE HEIGHT IN FEET (MAXIMUM = 5518)

>3000 <CR>

(5518 was determined to be the lowest cloud top in the subimage. You must enter a value less than or equal than 5518 as a default base.)

DO YOU WISH TO USE OA GRIDDED LCL DATA FOR BASE HEIGHTS?

>Y <CR>

(To use OA LCL data, you must have already created these values with GEMPAK routines. The data must be stored in a file in the current directory with a file name of OA_LCL.DATA.)

```
**** ROUTINE CAL_BOT_HGT ****

NOTICE  *** A TOTAL OF 20 CLOUD BASE TEMPERATURES
        *** WARMER THAN THE SURFACE TEMPERATURE.
        *** THESE LCL HEIGHTS WILL BE SET TO ZERO (0).
```

A summary message will now be displayed to your terminal. This message will also be stored in the diagnostic print file (DIAG_PRINT.FILE when diagnostics are selected) and can be printed using a VAX/VMS print command. A sample of this message follows:

```
 TTLH VALUES FOLLOW:

     1   291.4464    291.3600    -2.2503901E-04  0.0000000E+00
     2   291.3600    289.4600    -4.5008486E-04  384.0480
     3   289.4600    281.5600    -1.5989277E-03  4605.528
     4   281.5600    260.5600    -2.5660198E-03  9546.336
     5   260.5600    250.4600    -1.9818454E-03  17730.22
     6   250.4600    234.4600    -2.5669162E-03  22826.47
     7   234.4600    227.1600    -1.9424285E-03  29059.63
     8   227.1600    214.8600    -2.7926883E-03  32817.82
     9   214.8600    208.7600    -1.1319616E-03  37222.18
    10   208.7600    205.2600    -4.7177236E-04  42611.04


THE AVERAGE BASE HEIGHT FROM THE
RAW LCL DATA ARRAY IS:    9241.173

MAXIMUM CLOUD TOP HEIGHT IS:          46341.68
COMPUTED FOR A CLOUD TOP TEMP OF:  207.0000
THIS VALUE OCCURRED AT I/J:          60        72

AFTER COMPUTING ALL BASES, A TOTAL OF:     4081
CLOUD PIXELS HAD BASES THAT WERE LARGER THAN
THE CORRESPONDING CLOUD TOP HEIGHT.
THERE WERE        0 BASES SET TO ZERO(0)
BECAUSE THEY WERE LESS THAN THE SCALE FACTOR

THE AVERAGE DIFFERENCE WAS:    3152.64
THE TOTAL DIFFERENCE WAS: 12865921.00
AND THE AVERAGE BASE HEIGHT COMPUTED FROM LCL
DATA WAS:    5908.59

THE PERCENTAGE OF CONSISTENTLY DETERMINED
CLOUD BASE HEIGHTS WAS   57.36969%
OUT OF  9573.000     CLOUDY PIXELS.

THE CLOUD PICTURE ARRAY HAS BEEN WRITTEN
TO THE CLOUD_PICTURE.DATA FILE.
```

RUN THE PROGRAM MAKE_CLD_PICTURE TO DISPLAY THIS DIAGNOSTIC PICTURE SHOWING LCL BASE RESULTS.

The final output from INTCLD are three sets of files. These files are (For TEST1):

TEST1.BLO	TEST1.LOW
TEST1.BMI	TEST1.MID
TEST1.BHI	TEST1.HGH

The .BLO and .LOW files are the only files actually used in this example; however, the other four files are still created and must be kept on the system until after running CLDGEN. The purpose of these files is to store the values of the cloud base (.BLO) and cloud top heights (.LOW) that were computed in INTCLD.

APPENDIX A.4

USE OF CLDGEN

The program CLDGEN is used to create the Scaled Cloud Geometry Models (SCM). These files will contain the finite element (FE) representation of each connected group of pixels from the IR subimage. CLDGEN uses the cloud top base and height values that were computed by INTCLD. In this example, these values are read in from the .BLO and .LOW files (i.e. TEST1.BLO and TEST1.LOW) that were created by INTCLD. It is <u>not</u> necessary to be in the TAE command mode to run CLDGEN, so you may run this program on any of system. (system MICKEY usually works the best since MICKEY is generally the fastest.)

>RUN CLDGEN <CR>

DO YOU WANT TO USE TOPOGRAPHY DATA FOR THIS CLOUD MODEL (Y/N)?

>N <CR>

DEFAULT SCALING FACTOR IS 2.500000000-02

DO YOU WISH TO CHANGE THIS VALUE? (Y/N)

>Y <CR>

(The default value of .025 will give your clouds roughly a 4-to-1 vertical-to-horizontal scaling factor. A value of .05 results in roughly a 8-to-1 scaling factor.)

ENTER NEW SCALING FACTOR.

>.05 <CR>

Now the Low, Middle and High cloud data is processed. Messages will be displayed to your terminal such as:

<READING LOW CLOUD DATA>

<PROCESSING CLOUD NUMBER: 1

OF NODES FOR CLOUD 1 = 2682

<PROCESSING CLOUD NUMBER: 2

OF NODES FOR CLOUD 2 = 20

<PROCESSING CLOUD NUMBER: 3

```
# OF NODES FOR CLOUD       3  =  104

<PROCESSING CLOUD NUMBER: 4

# OF NODES FOR CLOUD       4  =  5

<READING MIDDLE CLOUD DATA>
<READING HIGH CLOUD DATA>

CLDGEN DONE
```

The number of nodes above refers to polygons that CLDGEN used to create each cloud model from the height data. CLDGEN will create four (4) files in this example. These files will be named:

TEST1.SCM;1   TEST1.SCM;2   TEST1.SCM;3   TEST1.SCM;4

Each file will contain the Parts, Nodes and Connectivity Array data that defines the geometry of a particular area of connected cloud pixels. This information is used by the MOVIE.BYU software to display a cloud in three-dimensions. An example of one of these geometry models follows:

TEST1.SCM;4

```
    1     5     4    12
    1     4
0.34000E+02 0.50000E+02 0.56250E+01  0.38000E+02 0.50000E+02 0.56250E+01
0.36000E+02 0.52000E+02 0.59375E+01  0.34000E+02 0.54000E+02 0.56250E+01
0.38000E+02 0.54000E+02 0.56250E+01
    1     4    -3     1     3    -2     2     3    -5     3
    4    -5
```

Where the first four values are:

a. The number of models, one (1) in this example.
b. The number of X, Y, Z coordinate points, five (5) in this example.
c. The number of polygons for this cloud, four (4) in this example.
d. The number of connection points for this cloud, 12 in this example.

The next two values are a repeat of value a. and value c. above (1 and 4).

The third set of values are the X, Y, Z coordinates for the FEs of this cloud model. Notice there are five (5) sets of X, Y, Z coordinates in this example.

The last set of values is the connectivity data that defines how to "put" this cloud together. The minus sign "-" indicates the last connection point for a polygon (FE). This file structure is also explained in the MOVIE.BYU Training Manual.

APPENDIX A.5

USE OF DISPLAY

This appendix gives an example of how to create a cloud scene using the MOVIE.BYU program called DISPLAY. The commands for every scene will be different depending on the total number of models that must be read in and displayed. Also, the MOVIE.BYU training manual explains how to use DISPLAY and the numerous options of this program. Notice, you must be in the TAE command mode for this routine to work.

1. Enter either **MOVIE_DONALD** or **MOVIE_GOOFY** depending if your working on the IP8500 or FD5000 graphics device.

2. At the **MOVIE MENU** prompt, enter "1" to: **READ in Model File**(s).

3. At the **Geometry File** prompt, enter "**TEST1.SCM;1**" This is the name of your first cloud geometry model file. After entering **TEST1.SCM;1**, enter two (2) more carriage returns; this will indicate to DISPLAY that no **Displacement File** and no **Scalar Function File** are being used. Each time the **MOVIE MENU** returns, enter "1" and your next cloud geometry model file (i.e. TEST1.SCM;2, TEST1.SCM;3, etc.) followed by two (2) more carriage returns. Continue this process until all your cloud geometry models are read in.

4. There are two geometry models that contain the flat surfaces used in this thesis. These models are stored in the files: **FLAT_SFC_64.MOD** and **FLAT_SFC_128.MOD** (the name is based on the desired resolution specified in DEFSCT). To "put" a flat surface below the clouds, read in the appropriate surface model using the same sequence of commands that were used above to read in cloud geometry models. Also, keep track of the model number because this must be used in other MENUs to give this model color and intensity.

5. At this point, you should define the default colors to all be white (like clouds). This could be done by using the **IMAGE MENU** options; however, a command file has already been created that does this for you automatically. To access this command file type: "**<COLORS**" and the necessary commands will be performed. This ability to create command files is a nice feature of DISPLAY and can save you time by letting you quickly read in a set of default commands you find your self entering over and over again (Section 2-7 of the 1987 MOVIE.BYU manual explains the echo command feature).

6. The following sequence of commands can be used to define the color for the flat surface.

a. First, enter "7" from the **MAIN MENU** to enter the **Hierarchical Structure Control** Submenu.

b. Then, enter "7" again to access to **Modify Copy Attributes** Submenu. Use the model number of the flat surface (ref. above) as the model number to modify.

c. Next, enter "**1**" to access the **Global** Submenu.

d. Finally, enter "**3**" to access the **Color** Command.

Now, set up the R(ed), G(reen), B(lue) color combination for the flat surface, a good combination is **0,0,1*** (i.e. blue). As you can see, this is a very time consuming process and using a command file here would probably save you some time. Note: command files can be modified using the standard VAX editor to change previous command files to match up with the commands needed for this display.

7. Use the following steps to define the intensity of the flat surface model:

a. Go back to the **Modify Copy Attributes** Submenu (by entering a carriage return), and enter "**2**" to access the **Shaded** Submenu.

b. Enter "**5**" to access the **Diffuse Light Intensity** command.

c. Now define your diffuse light intensity, a value of **0.95** was used for the blue surface in Fig. 9.

8. The same procedure that was just explained can also be used to define the **Diffuse Light Intensity** of the clouds. However, another option is to modify one of the command files that already have the "shell" of commands needed to automatically set up the intensity for a given number of clouds. In this example, the command file named **INT_FOR_25** was created and contains the necessary commands to defined the intensity for 25 clouds. (Just enter "**<INT_FOR_25**" to execute these commands).

9. Now that all the models have been given color and the desired intensity, you must specify the **Shaded** image and **Dithering** options in the **IMAGE CONTROL** Submenu. To do this:

a. first, enter **IMAGE** at the prompt. This "hard" command will automatically put you in the **IMAGE CONTROL** Submenu.

b. Now, enter "**2**" to enter the **Shaded** Image Submenu.

c. Finally, enter "**1,3**" to turn on the **Shaded Images** and **Dithering Toggle**.

10. The last step before displaying the image is to rotate the scene to the desired viewing perspective. This is accomplished with the following commands.

a. first, enter **VIEW** at the prompt to enter the **VIEWING CONTROL** Submenu.

b. Now, enter "**3**" to access the **Global Rotate** command.

c. At the **Global X, Y and Z Rotations** prompt, enter the desired rotation for this scene. Some of the rotations experimented with in this thesis were:

1. -90,0,0	to get a view from the south.
2. -90,-90,0	to get a view from the east.
3. 90,0,180	to get a view from the north.
4. -90,90,0	to get a view from the west.
5. -90,45,0	to get a view from the southwest.
6. -90,135,0	to get a view from the northwest.
7. -60,0,0	to get a view from the south with the scene sloping towards the viewer as seen in Fig. 9.

The MOVIE.BYU training manual explains the **Global Rotate** command in Section A-6. The important concept to <u>note</u> here is that <u>these rotations are additive</u> so that if previous rotations have been made, new values will add to them. Before entering a new view perspective, you must <u>clear the rotation by choosing the **Clear Global Transformation** command</u> in the **VIEWING CONTROL** Submenu.

11. Finally, the scene is ready to be displayed to the graphics device. This is the simple part. <u>Simply enter</u> **DI** and then <u>one more carriage return</u> to cause DISPLAY to display the image.

12. A feature that was added to DISPLAY and can not be found in the MOVIE.BYU training manual is the **SAVEIMG** option. This option allows you to save your image to a disk file after it is complete. To access this command either enter "**5**" within the **IMAGE CONTROL** Submenu, or just type "**SAVEIMG**" from any menu prompt. This routine will ask you to enter the filename to save this image to. After **SAVEIMG** is complete, control will be returned to the **IMAGE CONTROL** Submenu and you can create other scenes using the current geometry model configuration.

*These are the color combinations that were found through experimentation:

a. 1,0,0	Red
b. 0,1,0	Green
c. 0,0,1	Blue
d. 1,0,1	Pink
e. 1,1,0	Yellow
f. 0,1,1	Light Blue
g. 1,.5,1	Yelloworange.
h. .5,0,1	Purple
j. 1,.25,0	Orange
k. .25,.5,1	Sky Blue

APPENDIX B.1

DECODING NCDC, ASHEVILLE HISTORICAL SOUNDING DATA

This appendix explains the programs that were used to decode the NCDC, Asheville historical sounding data into GEMPAK format. There were four routines used in this process: ASH_SND_TAPE_DUMP, MAKE_STA_DATA, MAKE_SN_FILE, and MAKE_WBAN_ FILE. The steps required to go from a NCDC, Asheville historical sounding data tape to a GEMPAK sounding file are:

1. Mount the Asheville historical sounding data tape on the system using the foreign/nolab option, then run the program ASH_SND_TAPE_DUMP. This program will read every block of station data off the data tape and store this data in one file called ASH_SND.DATA. Example:

```
$ RUN ASH_SND_TAPE_DUMP
```

This routine is non-interactive. Just wait until it is finished and the data will automatically be stored in the ASH_SND.DATA file.

2. Run the program MAKE_STA_DATA. This routine will read through the data in the ASH_SND.DATA file and put the sounding for individual stations into a separate data file. Example:

```
$ RUN MAKE_STA_DATA

56000313184040800050
NUMBER OF RECORDS FOR THIS STATION =        50
56000313184040812 53
NUMBER OF RECORDS FOR THIS STATION =        53
5600031318404090030
NUMBER OF RECORDS FOR THIS STATION =        30
5600031318404091259
NUMBER OF RECORDS FOR THIS STATION =        59
5600031318404100053
NUMBER OF RECORDS FOR THIS STATION =        53
5600031318404101262
NUMBER OF RECORDS FOR THIS STATION =        62
5600031608404080045
```

This routine is also non-interactive. The information displayed to the screen list the first record of each sounding station and the number of levels for that particular sounding. An individual sounding data file will be put on the system for each station in the ASH_SND.DATA file. The names of these files are based on the WBAN code number and DTG information contained in the first

record of each sounding. For example, the WBAN and DTG of the first record above (highlighted) would result in a file name of: 031318404000.DATA to be put on the system, and all the sounding data for station number 03131 at 0000 UTC, 8 April 1984 will be stored in the 0313184040800.DATA file.

3. After the Asheville sounding data is on the system, this data still must be decoded and put into GEMPAK sounding file format. This process is accomplished by running the program MAKE_SN_FILE. The following example illustrates how to run this program.

```
$ RUN MAKE_SN_FILE

ENTER THE DATE/TIME/GROUP INFO -- YYMMDDHH (CHARACTER*8).
84040912

YEAR   = 84
MONTH = 04
DAY     = 08
TIME    = 00

IS THIS OKAY? Y(ES), N(O), OR E(XIT)
Y

ENTER LATITUDE OF NE CORNER POINT (F6.2 FORMAT).
USE POSITIVE FOR NORTH, NEGATIVE FOR SOUTH.
USE A BLANK HERE FOR A DEFAULT OF THE WHOLE NORTHWESTERN HEMISPHERE.
90.0

ENTER LONGITUDE OF NE CORNER POINT (F7.2 FORMAT).
USE POSITIVE FOR EAST, NEGATIVE FOR WEST.
-20.0

ENTER LATITUDE OF SW CORNER POINT (F6.2 FORMAT).
USE POSITIVE FOR NORTH, NEGATIVE FOR SOUTH.
20.0

ENTER LONGITUDE OF SW CORNER POINT (F7.2 FORMAT).
USE POSITIVE FOR EAST, NEGATIVE FOR WEST.
-180.0

NE LAT/LON PAIR IS:     90.00000       -20.00000
SW LAT/LON PAIR IS:     20.00000       -180.0000

ARE THESE OK? (Y/N)
y


ENTER THE WBAN FILE NAME.  DEFAULT IS WBAN_FILE.DATA

<CR>
```

PROCESSING SOUNDING FOR WEST PALM BEACH, FL

PROCESSING SOUNDING FOR CHARLESTON, SC

PROCESSING SOUNDING FOR TAMPA BAY, FL

PROCESSING SOUNDING FOR WAYCROSS, GA

PROCESSING SOUNDING FOR APALACHICOLA, FL

PROCESSING SOUNDING FOR CENTREVILLE, AL

In this example, when MAKE_SN_FILE is complete there will be a file created with the name SQUALL_DATA.84040800. This file will contain all the sounding data, within the requested region and at the specified time, in GEMPAK sounding file format. This file can now be used to create the objective analysis of pressure, potential temperature and LCL temperature values.

There is one other program that was written to aid in the process of creating GEMPAK sounding files from Asheville historical data tapes. The program is called MAKE_WBAN_FILE. The purpose of this routine is to allow one to generate (or add to) a file that is needed by the program MAKE_SN_FILE. The file is the WBAN_FILE.DATA file. This file contains WBAN code numbers and other identifying information about each sounding station throughout much of the western hemisphere. All sounding stations are identified by there WBAN code number on the Asheville historical sounding tapes. For this reason, a list of stations by code number must be used to control the processing of sounding data in the program MAKE_SN_FILE. An example of how to use this program follows:

$ RUN MAKE_WBAN_FILE

DO YOU WISH TO VIEW THE FILE? (Y/N).
Y

72203 12844 26.68N 80.12W PBI 21 WEST PALM BEACH, FL

72208 13880 32.90N 80.03W CHS 15 CHARLESTON, SC

72210 12842 27.70N 82.40W TBW 43 TAMPA BAY, FL

72213 13861 31.25N 82.40W AYS 47 WAYCROSS, GA

72220 12832 29.73N 84.98W AQQ 11 APALACHICOLA, FL

72229 03881 32.90N 87.25W CKL 140 CENTREVILLE, AL

ENTER THE STATION NAME. (L.E. 38 CHARACTERS, "END" = STOP, DEFAULT =
BUFFALO, NY

ENTER THE WMO CODE (IF KNOWN). (5 CHARACTERS, I.E. 72247, DEFAULT =
72247

ENTER THE WBAN CODE. (5 CHARACTERS, I. E., 03951,DEFAULT =
03951

ENTER THE LATITUDE -- 6 CHARACTERS, I.E., 32.35N, DEFAULT =
32.35

ENTER THE LONGITUDE -- 7 CHARACTERS, I.E., 094.65W DEFAULT =
094.65W

ENTER THE STATION ID -- 3 CHARACTERS, I.E., BUF, DEFAULT =
BUF

ENTER THE HEIGHT -- 4 CHARACTERS, I.E., 0202, DEFAULT =
0202

YOUR RECORD FOLLOWS:
72247 03951 32.35 094.65W BUF 0202 BUFFALO, NY

(A mistake was made here because the latitude was entered without an "N" to identify this value as north or south. To correct this mistake, answer no to the following question. Use a <CR> for the correct values and then re-enter the correct latitude .)

IS THIS GOOD? (Y/N)
N

ENTER THE STATION NAME. (L.E. 38 CHARACTERS, "END" = STOP, DEFAULT =
BUFFALO, NY

<CR>

ENTER THE WMO CODE (IF KNOWN). (5 CHARACTERS, I.E. 72247, DEFAULT = 72247

<CR>

ENTER THE WBAN CODE. (5 CHARACTERS, I. E., 03951,DEFAULT = 03951

<CR>

ENTER THE LATITUDE -- 6 CHARACTERS, I.E., 32.35N, DEFAULT = 32.35
32.35N

ENTER THE LONGITUDE -- 7 CHARACTERS, I.E., 094.65W DEFAULT = 094.65W

<CR>

ENTER THE STATION ID -- 3 CHARACTERS, I.E., BUF, DEFAULT = BUF

<CR>

ENTER THE HEIGHT -- 4 CHARACTERS, I.E., 0202, DEFAULT = 0202

<CR>

YOUR RECORD FOLLOWS:
72247 03951 32.35N 094.65W BUF 0202 BUFFALO, NY

IS THIS GOOD? (Y/N)
Y

ENTER THE STATION NAME. (I.E. 38 CHARACTERS, "END" = STOP, DEFAULT =
BUFFALO, NY
END

WANT TO SEE THE OUTPUT FILE? (Y/N)
N

WANT TO WRITE NEW DATA? (Y/N)
Y

DONE BUILDING WBAN_FILE. FILE UPDATED..

Now this file can be used as input to the routine MAKE_SN_FILE.

APPENDIX B.2

GENERATING THREE-DIMENSIONAL SURFACES

This appendix explains the steps required to generate a three-dimensional geometry model for a pressure height surface. The same sequence of events also applies to potential temperature surfaces.

1. First, use the GEMPAK objective analysis (OA) routines to create an OA of the heights of a desired pressure level over the geographic region of interest. For instance, if one desires to display the 850 mb surface in three-dimensions, then specify LEVEL = 850 and PARMS = HGHT within the GEMPAK routine SNBANL. You will also need to specify the name of the OA file in GEMPAK routine OAGRID. For this example, the name of the file was 850_HGHT.84040912.

2. After the above file has been created, run the program 3D_LAYER. Example:

```
$ RUN 3D_LAYER

ENTER NAME OF GRIDDED DATA FILE (WITH EXTENSIONS).
850_HGHT.84040912

START I & J ARE:    32      297
ISIDE IS:           64

ENTER TYPE OF LAYER TO CREATE L(OW), M(IDDLE), OR H(IGH)>
M

WRITING OUT THE BASE HEIGHTS ............
FINISHED WRITING THE BASE HEIGHTS...

WRITING OUT THE TOP HEIGHTS ..............
FINISHED WRITING THE TOP HEIGHTS .....
```

This program will put two files on the system that contain the base and top height values for the 850 mb surface over the region of interest. In this example, the files will be named TEST1.BMI and TEST1.MID. Notice that these files have the same qualifier (TEST1) as the TEST1.BLO and TEST1.LOW files in the example of how to run INTCLD (Appendix A.3). The pressure height values are actually treated as a "cloud" layer within CLDGEN, and the current code can only handle three (3) layers at a time. Therefore, CLDGEN can only create the geometry files for three separate data sources at a time. For example, you could create one more layer of values for TEST1 (i.e. 700 mb heights) and treat them as a (H)igh layer of data. Then when CLDGEN is run, the geometry files for the clouds, 850 mb heights and 700 mb heights would all be created at one time.

3. Now that the height data files have been created, run the program CLDGEN. There is no difference in the procedure used here than the example procedure given in Appendix A.4. However, note that one extra geometry file is created (TEST1.SCM;5), and this file contains the geometry model for the 850 mb surface. Example:

```
$ RUN CLDGEN

< DO YOU WANT TO USE TOPOGRAPHY DATA FOR THIS CLOUD MODEL (Y/N)?
N

DEFAULT SCALING FACTOR IS   2.5000000E-02
DO YOU WISH TO CHANGE THIS VALUE? (Y/N)
N

<READING LOW CLOUD DATA>

<PROCESSING CLOUD NUMBER: 1

# OF NODES FOR CLOUD        1 = 2682

<PROCESSING CLOUD NUMBER: 2

# OF NODES FOR CLOUD        2 = 20

<PROCESSING CLOUD NUMBER: 3

# OF NODES FOR CLOUD        3 = 104

<PROCESSING CLOUD NUMBER: 4

# OF NODES FOR CLOUD        4 = 5

<READING MIDDLE CLOUD DATA>

<PROCESSING CLOUD NUMBER: 5

# OF NODES FOR CLOUD        5 = 4352
<READING HIGH CLOUD DATA>
CLDGEN DONE
```

APPENDIX C

CREATING SHADOW SCENES

This appendix explains the procedure used to create the shadow scenes displayed in this thesis. All the details for defining a light source and setting up the shadow intensity are defined in the MOVIE.BYU training manual (see pages A-8, A-19 and A-33). However, the following routines are used to determine the vectors that are needed in the **Lightsource Control** Submenu, which is used to create shadow scenes. Run the following programs:

```
RUN      FIND_BIG_Z

ENTER GEOMETRY FILE WITH EXTENSIONS C*18
test26.scm;8

NO. OF PARTS        =     1
NO. OF NODES        =     10349
NO. OF ELEMS        =     9865
NO. OF CONS         =     39274

PLEASE WAIT WHILE I PROCESS       5174 RECORDS

THE LARGEST Z VALUE WAS:    57.81300
THIS OCCURRED AT X/Y LOC:   236.0000      228.0000

$ RUN CAL_SUN_LOC

ENTER WEST MOST LONGITUDE (+)
88.3

ENTER EAST MOST LONGITUDE (+)
72.85

ENTER TALLEST CLOUD HEIGHT (FEET)
464 342

ENTER MODEL HEIGHT OF TALLEST CLOUD (UNITS)
57.813

ENTER ZENITH ANGLE (DEGREES FROM THE Z AXIS)
62.54

ENTER AZIMUTH ANGLE (DEGREES FORM THE EAST)
-18.76
```

ENTER # OF MODEL UNITS FOR THIS MODEL
508

ENTER # OF PIXELS IN THIS SCENE (64, 128,..)
256

SHADOW ON EARTH IS: 27022.45 METERS

EARTH METERS/MODEL UNITS ARE: 1689.768

MODEL SHADOW LENGTH IS: 15.99181 UNITS
MODEL THETA VALUE IS: 1.300931 DEGREES

THE X LIGHT VECTOR POINT IS: 254.0000
THE Y LIGHT VECTOR POINT IS: -86.27083
THE Z LIGHT VECTOR POINT IS: 918.2515

These three light vector points are to be used as input to the X, Y, Z values requested when using the **Lightsource Control** Submenu within the **Viewing Control** Submenu of **DISPLAY**. It is important to note here that these vectors are only approximate and will only give realistic shadow lengths for cloud scenes that are viewed from directly overhead. That is, the lightsource does not move with the scene as the scene is rotated, rather the lightsource remains fixed in space.

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